AUTOMATED STORAGE AND RETRIEVAL SYSTEM (AS/RS)

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Electrical and Automation Engineering

Valkeakoski, Autumn 2020

Nhat Tran and Dung Nguyen

ABSTRACT

Electrical and Automation Engineering
Valkeakoski

Author Nhat Tran and Dung Nguyen **Year** 2020

Subject Automation Storage and Retrieval System (AS/RS)

Supervisor(s) Juha Sarkula and Mika Oinonen

ABSTRACT

Automation Storage and Retrieval systems (AS/RS), in comparison with the manual storage systems, have been more efficient and feasible in terms of labor and workforce. The rapid thriving of the AS/SR technology offers a wider range of size, cost and flexibility when it comes to a considerable investment of any company or industry. Commissioned by a steel company, the main objective of this thesis project was to design and implement a small-scale demo model of AR/RS, following the guidance of the company's supervisor.

Time planning and work were distributed evenly throughout the project between the authors. In order to select the most suitable components, a data table on the specifications of the devices chosen from a variety of manufactures was made. This thesis includes two main parts: First, the mechanical part was drafted to build a backbone for the whole project. The second part includes the use of electrical components and the PLC Siemens S7-1200, which can be considered as a heart of the system. Expertise in electrical wiring design and automation engineering was required in the project. Literature on AS/RSs was used as sources.

Conclusively, the outcome of the thesis project was a successfully assembled AS/RS model, which met the requirements of the commissioning party regarding size, cost and implementation after being tested. The model will be expanded and will serve for visualization and training purposes of the commissioning party in the future.

Keywords AS/RS, Linear Motion, PLC, stepper motor

Pages 90 pages including appendices 6 pages

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Objectives of thesis project

Despite the fact that manual warehouses show a variety of deficiencies in safety, precision, and efficiency, many companies, including the commissioning party are still using manual warehouses since they are inexpensive and versatile in a short-term period.

The commissioning party is a heavy industrial steel production company that requires transporting especially heavy objects. During the production of bars/rods steel, breakdown of the mechanical and electrical equipment occurs frequently and, by the same token, some of the devices are outdated. Mostly, new components used for replacement are stored in a traditional warehouse of the company. Another manual warehouse is responsible for storing the broken parts and outdated components, which are scrapped or disassembled into other distinct components or even refurbished for later use. The primary tools for moving and lifting heavy materials are forklifts and crane systems, which are inefficient and dangerous for warehouse employees. Therefore, the commissioning party is planning to enlarge the scale of their storage system. They have been conducting various long-term projects and research before taking investments into consideration since designing such a system in practice is extremely costly. The main goal of the company during this process is to increase precision, speed, safety measures and reduce the amount of work for operators and employees.

One of the commissioning party's projects is designing a mini-scale demo of Automated Storage and Retrieve Systems (AS/RSs) and this project was within the scope of this thesis. The target of the project was to successfully finalize the AS/RSs demo (described in Chapter 4) for the experimental use of the commissioning party. The difficulties in conducting the thesis included making use of all mechanical and electrical parts because all of the components used in this project were from excess equipment provided by the company. Accordingly, the demo might not be entirely similar to AS/RSs in practice, but it was to deliver a basic overview of their structure and operation. Furthermore, the demo, if being tested successfully, was to be arranged as a part of the training program for new employees or internships to approach the devices and components in the company.

1.2 Scope of thesis

The thesis covers the fundamental knowledge of automation in general and in AS/RSs in practice, thus understanding what the disadvantages of the warehouses without automation are, also, what the importance of the AS/RS in the warehouse is. For the experimental design, the thesis mentioned what perspectives of AS/RSs such as structure, programming is described to design the model and what difficulties the authors had come up with the components and the mechanism. At the end of the thesis, the experimental results conclude what the final target is as well as what the model improvements and advice for the commissioning party are.

1.3 Task division

Chapter 1 gives a glance at the overall purpose of the thesis. The theoretical knowledge and research for the thesis, especially automation in AS/RSs and their components, are explained in chapters 2 and 3. Chapter 4 describes the operation mechanism of the AS/RS model used in this thesis. Chapters 5 and 6 concentrate on the details of the programming and user-interface of the model. Finally, chapter 7 proposes some advice and improvements for the current AS/RS model.

The thesis peoject was conducted and written by two authors, who shared chapters in the thesis writing. Nhat Tran has written chapters 1, 2, 5 and Dung Nguyen has handled chapters 3, 4, 6. Chapters 7 and 8 were equivalent work between the two authors.

2 THEORETICAL BACKGROUND

Chapter 2 describes the theoretical background of automation, Automated Storage and Retrieval Systems (AS/RSs) in practice and the fundamentals of Programmable Logic Controllers (PLCs) programming languages.

2.1 Automation system

In this chapter, automation in general and in traditional warehouses are defined. This chapter also highlights the disadvantages of the warehouses without automation

2.1.1 Automation in general

“Automation can be defined as the technology by which a process or procedure is accomplished without human assistance. It is implemented using a program of instructions combined with a control system that executes the instructions. To automate a process, power is required, both to drive the process itself and to operate the program and control system. Although automation is applied in a wide variety of areas, it is most closely associated with the manufacturing industries.” (Groover, 2016, p. 75). The term "automation" was originally invented in 1946 by an engineering manager at Ford Motor company. An automated system three distinct parts: Power, Program of instructions, Control System.

The term "Power" refers relatively to electric power or electricity, which are utilized for managing the process and operating the automation system. The process is the manufacturing procedure that is, for instance, material handling or transportations between different operations. In an automation system, "Power" is also required for the controller units (computers), control signals (sensors, actuators) and data acquisition systems. Program of Instructions consists of multiple steps in the procedure of the manufacturing operation, which are displayed in a Work Cycle Program. Control System performs the execution of the manufacturing operation based on the Program of Instructions. A system can be either an open-loop control system or a closed-loop control system. With the help of Computer Process Control (the use of digital computers), the process of Control System in different industries has become faster and more accurate. There are different tools for controlling the process, for instance, Programmable Logic Controllers (PLCs), Remote Terminal Unit (RTU), Direct Computer Process Monitoring, Computer Numerical Control (CNC), Supervisory Control and Data Acquisition (SCADA), Distributed Control System (DCS), etc. (Groover, 2016, pp. 110-116). PLC is the controller used in this project.

Automation in manufacturing is categorized into three types: fixed automation, flexible automation and programmable automation (Groover, 2016, p. 79). The association between the three types depends on the variety and quantity of the products as displayed in Figure 1. Fixed automation is generally fully automated systems, while programmable automation is usually half-automated systems and flexible automation is the mixture or combination of the other two types.

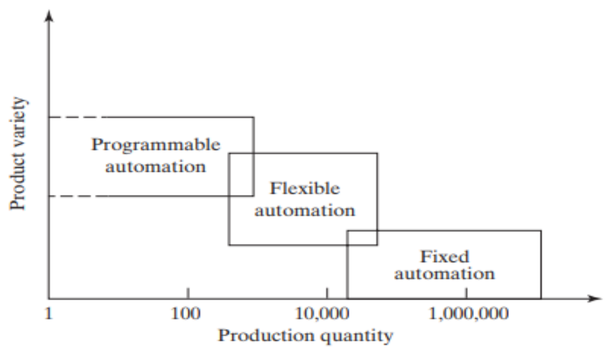


Figure 1. Relation between automation and variety/quantity of product (Groover, 2016, p. 8)

Automation since 1946 has been rapidly rising along with the development of integrated circuit, microprocessor technology and the variety of forms of the Computer Process Control System (Groover, 2016,

p. 76). Automation nowadays not only boosts productivity and efficiency by operating uninterruptedly, but also diminishes the errors and the dependence on human workers. Considering human factors and ergonomics due to distraction, negligence, or exhaustion, the probability of error occurrence is high, thus interrupting the workflow and managing process.

2.1.2 Automation in warehouses

Storing and retrieving goods in a warehouse or distribution center is a common and traditional concept. Storage/warehouse systems are diverse, but there are two types: manual and automated in terms of operation. According to the Peerless Research Group, only 4% of them are highly automated (Logistics Management, 2019). The rest are mostly manual and half-automated, where operators move around the facility, lift each product by forklifts and pick up by hand. The main drawback of manual storage systems is that they are dependently labour-intensive and non-computerized. They involve many moving pieces and heavy machinery other than forklifts controlled by storage/warehouse workers.

Inaccurate counts and misplacement might result in time-wasting and running out of essential items for new orders. Moreover, there is a possibility that employees encounter injuries as more than 5% of traditional warehouse workers were injured in 2016 (Conveyco, 2019). Manual storage/warehouse systems, despite their simplicity and low-cost investments, cannot optimize the space and capacity of the warehouse regarding height due to limited reach of forklifts, thus occupying the considerably large land area. In manual storage systems, numerous products are usually stacked up one on top of another, which might reduce the quality of some at the bottom. Because of the lack of automation and computerization, it is very challenging to track the inflow and outflow of each product and its quantity. Therefore, each product transaction needs to be monitored continuously to maintain its availability and stocking levels. The tracking and monitoring information are not shared within any automated systems or programs, thus accumulating the wastes of time and labour and making the whole process more cumbersome.

Most businesses nowadays are still utilizing manual storage systems, despite their unproductivity. The initial investment and further maintenance costs are low; the training program is simple for employees. The manual system is especially appropriate for small businesses because of their simple product supply chain. For larger businesses, operating storages manually possibly gain a lot of short-term benefits in the early stage. However, the accumulation of errors and time-wasting will decelerate business development gradually. Moreover, storing heavy products in a traditional warehouse requires many forklifts and crane systems. All lifting and moving are handled by many human workers. Therefore, the possibility of causing a serious incident is high.

2.2 **Background of AS/RS**

This chapter focuses on a closer look at the structure and operation of the AS/RSs in real life.

2.2.1 General description

Industrialization is the key to push economic growth as the number of goods produced has been proliferating. In order to suffice for mass-production, modernizing storages/warehouses are necessary for big companies and businesses. New innovated technology, such as Automated Storage and Retrieval Systems (ASRS), enables businesses to keep up with the increasingly fast and demanding market. AS/RSs can be briefly described as a combination of equipment and supervisory control systems, which automatically place and pick items within the warehouse facility. In a broader range, AS/RS equipment consists of parallel aisles, racks, S/R (storage/retrieve, also called stacker crane) machine. Expanded AS/RSs also include conveyors, I/O (input/output) stations, and P/D (pick/delivery) stations (Manzini, 2012, p. 162). AS/RSs is just one of the integrated systems of the warehouse and not an entire warehouse, which is shown in Figure 2.

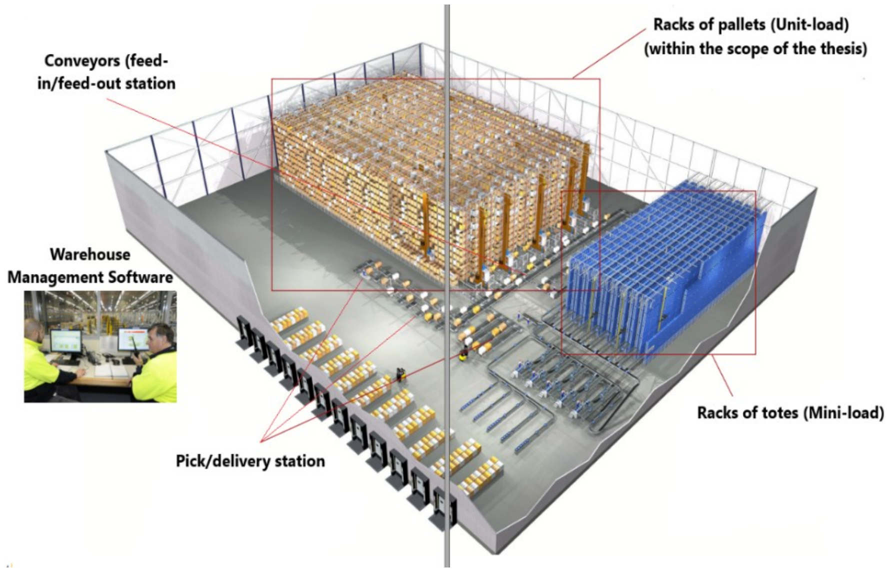


Figure 2. General AS/RS in real life (Dematic, 2016, pp. 4-5)

Racks are steel structures of accumulated cells, where each load is stored in a cell. S/R machine is an autonomously electromechanical system that moves and lifts loads within an aisle, which is the space between two racks. I/O station is placed next to the S/R machine and connected with the conveyors, where incoming/outcoming loads are transported and ready to be stored/retrieved. P/D station is located at the other end of the conveyors, in which items are manually picked by workers and ready to be stored/delivered. AS/RS storing procedure operates initially at the P/D station, where items are classified by size/weight and assigned to trays or pallets. For safety reasons, the loads are scanned again to ensure that loads are within weight limits and pallet loads do not exceed the size limit. Scanned loads are then routed to the I/O station, where the supervisory control system detects and automatically assigns to an arbitrarily available storage location in the rack and saves the location in its memory. The operators can also select a specific location in the rack when there is a request for that specific item. After the detecting and assigning procedure, the S/R machine picks up the loads from the I/O station and place them into a cell of the rack. AS/RS retrieving procedure operates relatively the opposite of the storing procedure. The operator selects a requested location for retrieving and the memory of that location will be removed from the system. The S/R machine moves the load from the rack onto the I/O station. From here, there are a certain amount of conveyor lines for retrieving loads. There is always a conveyor line for transporting loads to the P/D station for delivery. Usually, there is also an additional line for moving loads from one rack to another and a line for loads to be discarded or withdrawn from the warehouse (Manzini, 2012, p. 163).

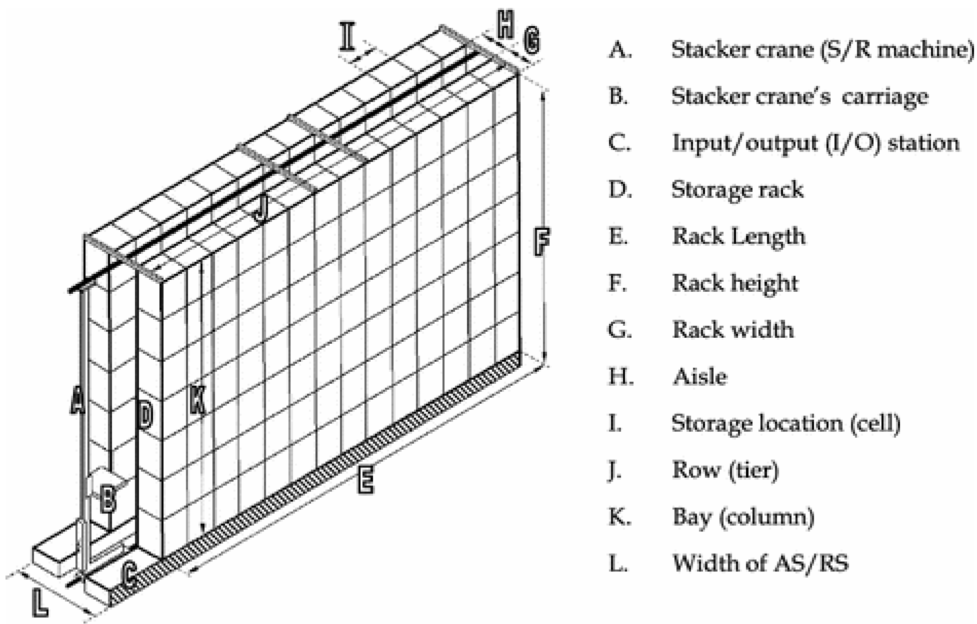


Figure 3. General structure of an AS/RS (Manzini, 2012, p. 203)

2.2.2 Structure and depth

Rack and aisle: There are various options for designing the structure of rack and aisle, enormously depending on the dimension of the system and the area of the warehouse. The simplest AS/RS accommodates a single-wide aisle and a single-deep rack type (shown in Figure 4), which are placed alternately next to one S/R machine, and two racks must not be placed next to each other. On the other hand, AS/RS with a double-deep rack contains two racks located next to each other, and AS/RS with double-wide aisle contains two S/R machines placed next to each other (Manzini, 2012, p. 202). In general, a structure with more than two consecutive racks or two consecutive S/R machines is called a multi-deep rack or a multi-wide aisle (classified as Deep Lane AS/RS).

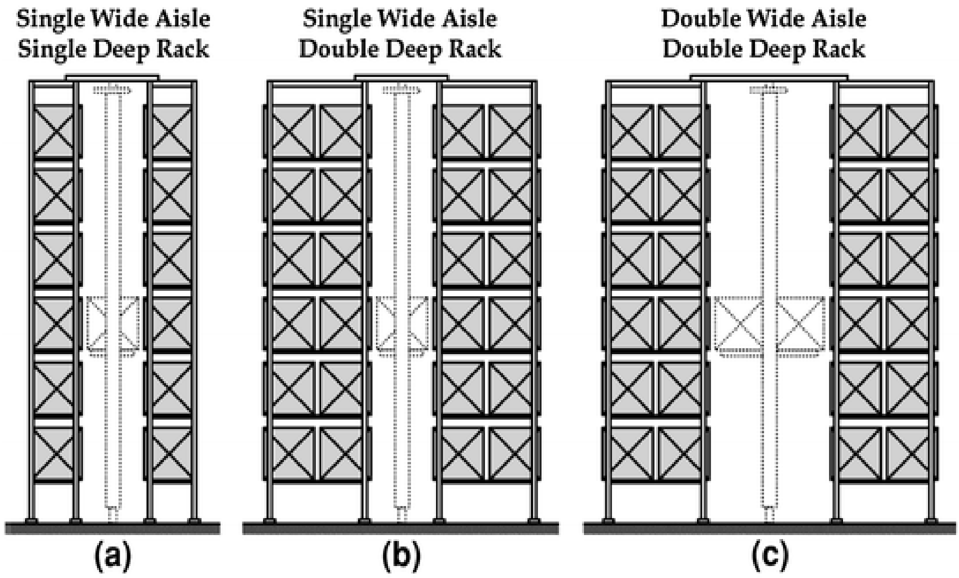


Figure 4. Width and depth structure of rack and aisle (Manzini, 2012, p. 203)

S/R machine is a cuboid geometry robot that contains two shuttle drives and a carriage as can be seen in Figure 5. S/R machine transports loads horizontally and vertically along the aisle from its carriage to a specific cell. The structure of the S/R machine is comparable to that of the rack and aisle. Depending on the rack and aisle structure, there is a variety of choices for designing the location and the number of S/R machines as shown in Figure 6. More S/R machines increase the cost but boosting efficiency.

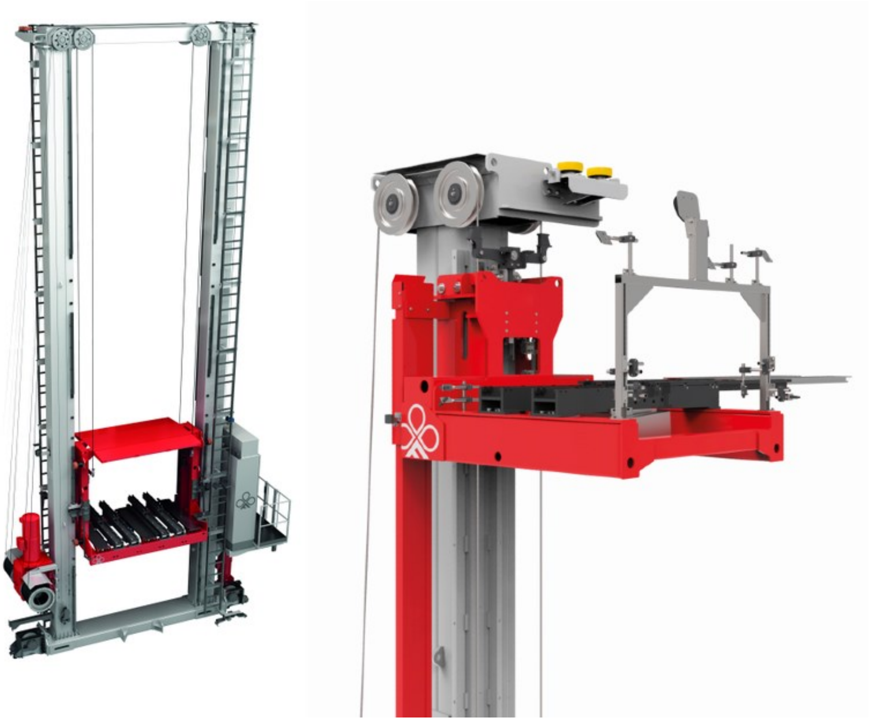


Figure 5. S/R machine (Ferretto Group, 2019)

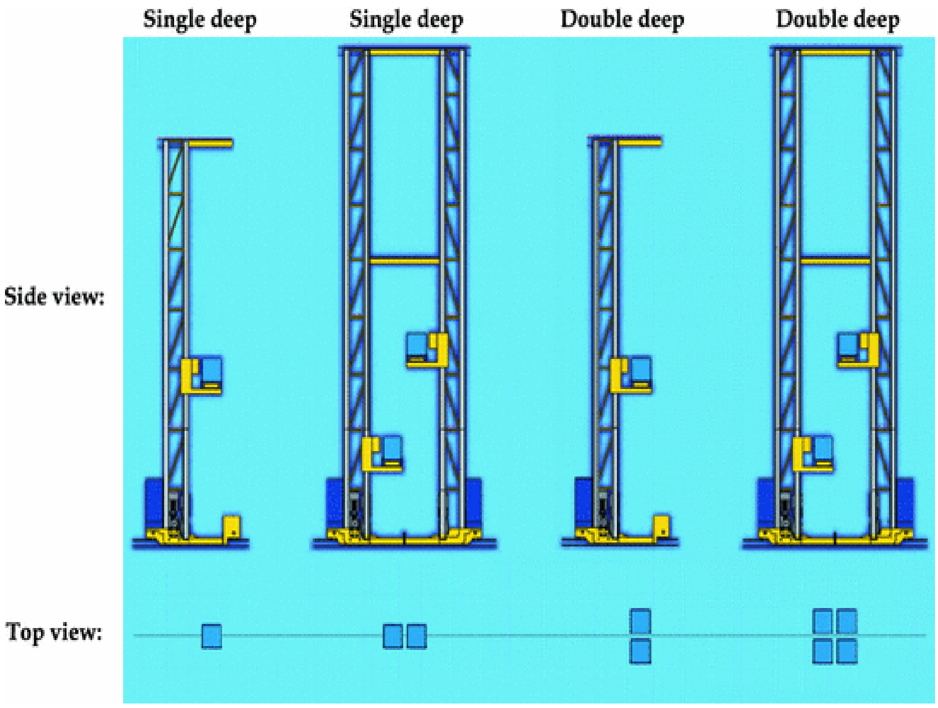


Figure 6. Some structure types of the S/R machine (Manzini, 2012, p. 167)

2.2.3 Common types of design

Unit-load AS/RSs are the most common type of system used to store large and standardized loads, typically on pallets. Unit-load AS/RS includes shuttle system, telescopic forks and single/multi-layer rack-aisle structure. The shuttle system is controlled by computer supervision, in which a tall mast carries a crane of each load horizontally and vertically at high speed along the rail through the aisle for placing and retrieving. The handling mass is up to 1500 kilograms per load and can reach up to 40 meters.

Figure 7. Unit-load AS/RSs on pallets (Ferretto Group, 2019)

Mini-load AS/RSs are used for storing small loads such as individual tools, parts that are contained in boxes, trays or cartons. Relatively similar to Unit-load AS/RS, Mini-load AS/RS uses telescopic forks within the single/multi-layer rack-aisle structure. Since items are much smaller, the system will typically use a suction cup, robotic arms or extractors. Unit-load ASRS can handle up to 500 kilograms per load and rack structure can be up to 25 meters.

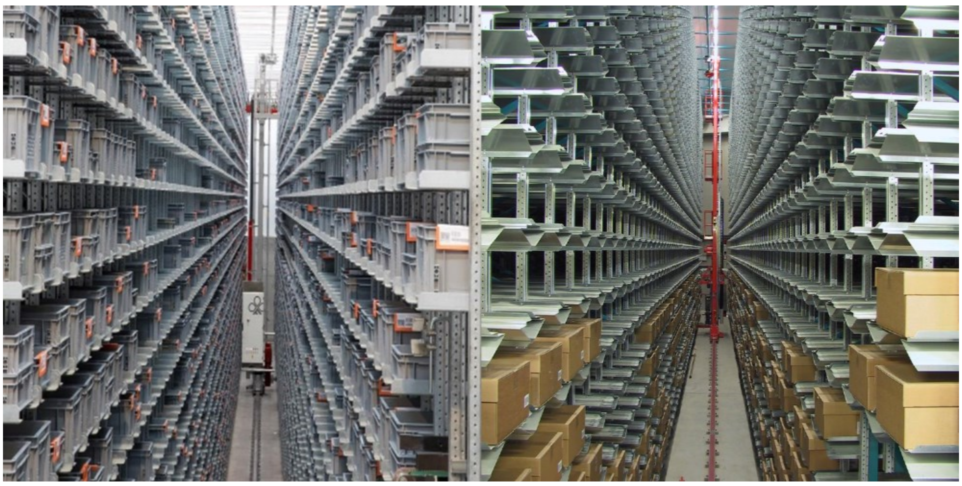


Figure 8. Mini-load AS/RSs on trays and cartoons (Ferretto Group, 2019)

Deep lane AS/RS is a fully automatic and high-density storage system used for storing a large number of accumulated loads. Deep lane AS/RS is composed of rack structure, satellites, shuttle carriers, pallets, lifts and conveyors. Each rack is a flow-through design with two different modes: first-in-first-out (FIFO), where shuttles flow in on one end of the rack and flow out on the opposite end; last-in-first-out, where shuttles flow in and out at only one end of the rack. Loads are only accessible at one or two sides depending on the rack structure. Shuttle carrier can handle a loading capacity of 1500 kilograms and travel at a maximum speed of 2 m/s.

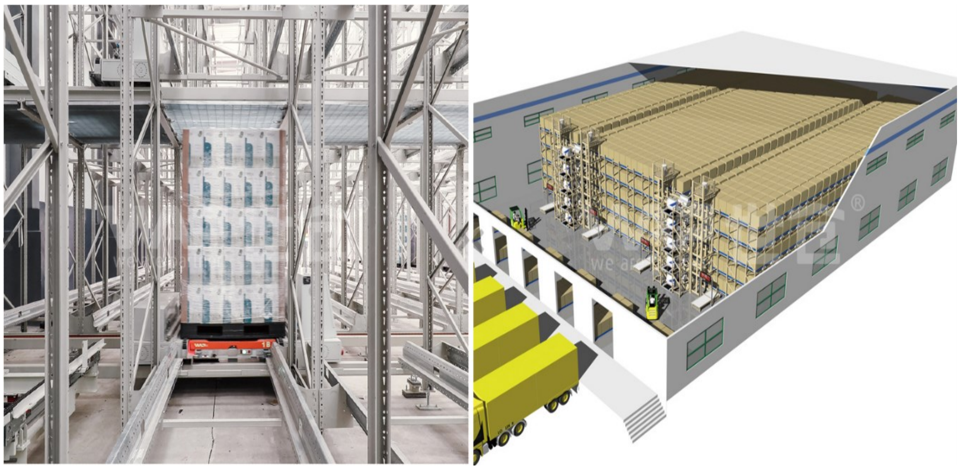


Figure 9. Deep lane AS/RS (multi-depth) **-** (WAP, 2018)

2.2.4 Challenges of designing AS/RS

The main reason for the fact that most warehouses nowadays are implementing in a traditional way, is the complexity of AS/RSs. With the immense cost of the components and the handling system, it is critical to efficiently design an AS/RS that meets the current and projected future requirements. The physical structure of AS/RSs is inflexible, the cost for moving the system is considerably costly. Thus, it is decidedly necessary to design it carefully on the first try. Since AS/RS is a part of the warehouse, not only does it have to operate efficiently within the system itself, but also it must be compatible with other systems within the warehouse. In other words, the performance measurement of the AS/RS must also be considered associated with the rest of the warehouse (Manzini, 2012, p. 167). Other factors of designing constructive AS/RSs in practice such as feed in/feed out system, controlling software, WMS (Warehouse Management System), Travel-time, Warehouse planning, Data/Economic Analysis and performance measurement were not within the scope of this thesis project.

2.3 **Programmable Logic Controllers (PLCs)**

This chapter illustrates the main PLC programming languages and the difference among them as well as the structure of the program (specifically in TIA Portal).

2.3.1 Definition

“A programmable logic controller (PLC) can be defined as a microcomputer-based controller that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting, and arithmetic functions through digital or analog input/ output (I/O) modules, for controlling machines and processes.” (Groover, 2016, p. 256)

2.3.2 Programming languages

Programming is the method, in which the control instructions through the programming device are provided to the PLC. Including logic expressions, sequences, counting and timing, control instructions are represented in different programming languages. According to the International Electrotechnical Commission - IEC 61131-3 standard, there are five PLC programming languages, three graphical and two text-based languages, respectively Ladder Diagram (LD), Sequential Function Charts (SFC), Function Block Diagram (FBD), Structured Text (ST), Instruction List (IL). LD, SFC, and FBD are graphical type language, ST and IL are textual based language. “IEC 61131–3 also states that five languages must be able to interact with each other to allow for all possible levels of control sophistication in any given application.” (Groover, 2016, p. 260)

Structured Text (ST) is a high-level language containing lines of codes separated by the semicolon and different keywords (FOR, WHILE, IF, ELSE, ELSIF, CASE, ETC.) that is similar to the C language. The principal feature of ST language is the capability to execute complex tasks such as mathematical calculation and algorithms. These tasks when constructed in other graphical languages might look extremely messy and convoluted. Instruction List (IL) is a low-level language, which contains a series of instructions of the relationships between the components and each rung of the ladder diagram. Function Block Diagram (FBD) is a graphical language consisting of separately connected functional blocks, where each block describes the relationship of the inputs and outputs. FBD technically works well with motion controls and visually is easy to understand. However, FBD can be very disorganized to troubleshoot as the blocks can be placed anywhere in a single line (network). Sequential Function Chart (SFC) is identical to the flow chart. SFC displays a sequence of steps and transitions that move from one state of the system to another by setting the conditions to true or false. SFC among other types is easy to construct and troubleshoot, although it does not fit all applications.

Ladder Diagram (LD) is currently the most widely used PLC programming language, which looks similar to the electrical schematics going vertical. Constructed as a ladder structure like the rails and rungs, LD expressed the logic operations such as sequential, counting, timing, mathematical problems via symbolic notation. The symbols and order of execution from up to down, left to right make the ladder logic readable and easy to understand. Electricians and shop personnel without being familiar with computer programming can understand the logic of LD more easily than other types. The drawbacks of LD are difficulties in configuring motion control and handling complex mathematical functions and algorithms. These issues can easily be resolved with the help of other types of PLC programming languages.

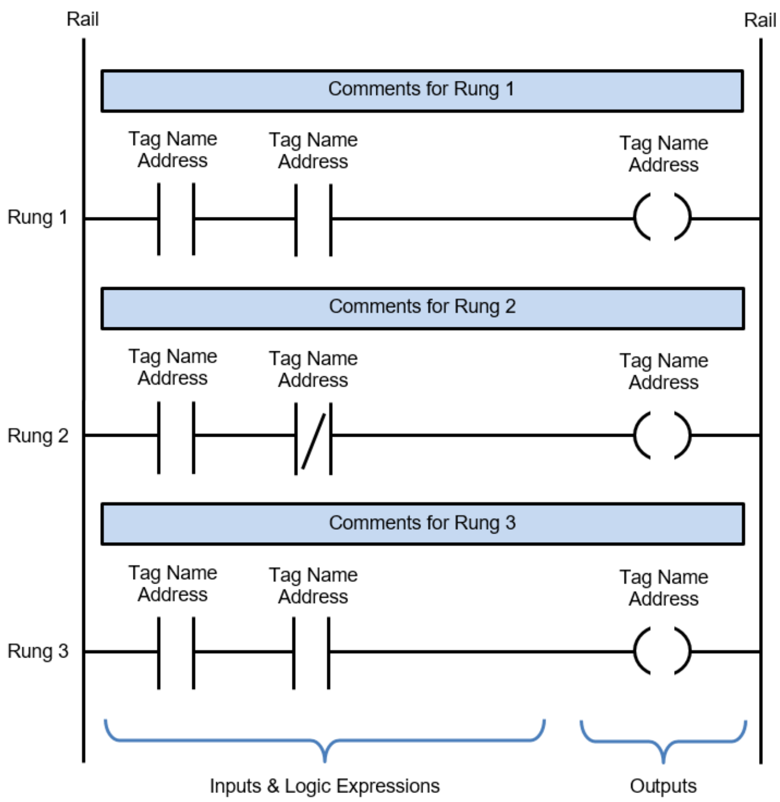


Figure 10. Structure of ladder logic diagram (Ladder Logic WORLD, 2020)

In the TIA Portal program in this thesis, the programming language used is Ladder Logic Diagram (LAD notation in TIA Portal). Within the program, the mostly used logic operations are “Assignment”, “Set”, “Reset” outputs.

“Assignment” output activates the pulse to the output coil (set the output to “1”) whenever the input signals are “1”. In other words, the value of the “Assignment” output depends on the values of the inputs.

Figure 11. Symbol of “Assignment” output in LAD (TIA Portal)

“Set” and “Reset” output usually work as a pair as they both control the same output. Once the output is set (“1”), it will remain unchanged unless the output is reset (“0”) and vice versa. Therefore, it is essential to manage in a large project where the output is set and where the output is reset

Figure 12. Symbol of “Set” output in LAD (TIA Portal)

Figure 13. Symbol of “Reset” output in LAD (TIA Portal)

2.3.3 Program blocks

In industrial manufacturing, it is essential to divide the automation process into individual and simpler tasks. Accordingly, the key to organizing the structure of the program is to break it down into different and self-contained sections also known as program blocks. Each block clarifies a specific function of the program, thus making the entire programs more organizable and easier to understand. Also, debugging and later modifications will be much simpler.

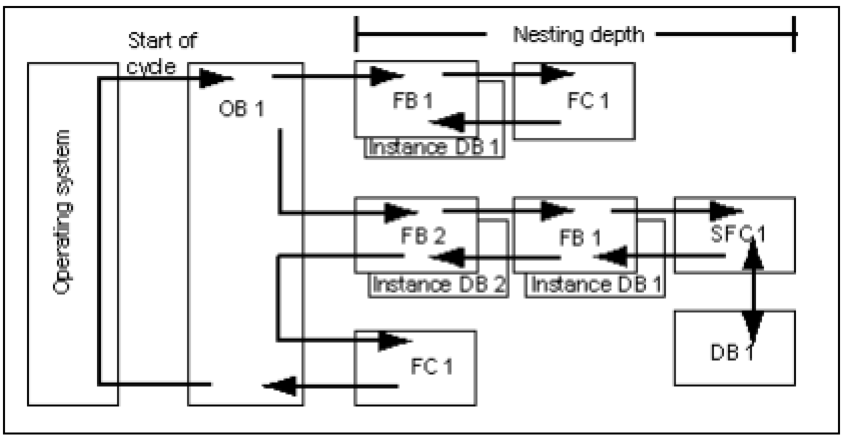


Figure 14. Call hierarchy of program blocks (Siemens, 2017)

Organization blocks (OBs) also known as the main block of the program create the structure of the interface between the user program and the operating system. A "Program cycle" OB executes cyclically and contains the instructions to call the other blocks of the program.

Function blocks (FBs) are logic blocks with memory functionality. The static variables and the parameters that migrate to the FB are stored in the instance DB. When the execution of the FB is complete, data saved in the instance DB are not lost. On the contrary, temporary variables, which are stored in the local data stack are lost after the execution of the FBs. Function blocks are used for the complex and frequently occurring program.

Functions (FCs) are logic blocks without memory functionality. Temporary variables in the FC saved in the local data stack are lost after the FC's execution. Shared data blocks can also be used to save data permanently. Moreover, FCs are often applied in high frequently used tasks, which executes by different logic blocks' call.

Data blocks (DB) DBs, in contrast to logic blocks, are areas for storing user data. In addition, shared data blocks assigned to a function block can be accessed by all other blocks. The size of DBs can differ based on the CPU maximum size.

3 BACKGROUND AND SELECTION OF HARDWARE

This chapter provides fundamental knowledge in mechanical and electrical fields. Additionally, the selection of material and components is explicitly discussed throughout the whole chapter.

3.1 Mechanical section

In this mechanical section, chapter 3.1.1 focuses on comparing materials used for the shelves. Whereas chapter 3.1.2 mainly presents fundamental concepts of linear motion. Later, the choice of mechanical components is mentioned in chapter 3.1.3 and 3.1.4.

3.1.1 Material selection

Throughout history, steel and aluminium are the two most common materials used in the construction, aerospace, home appliances, and especially the mechanical and metalworking industries. Each material has distinct characteristics suitable for different applications. Cost, flexibility, environment resistance, and application play an essential part in choosing the project's material.

The cost is always an essential factor to consider when buying any product. Steel is usually cheaper than aluminium due to the lower price of raw material. However, aluminium is preferable because of the malleable and anti-corrosion abilities. Moreover, aluminium is easier to work with. Unlike steel, an equal-dimension piece of aluminium can withstand the same limit test without cracking or tearing during spinning (Wenzelmetalspinning, n.d.). Accordingly, aluminium was chosen for the project frame.

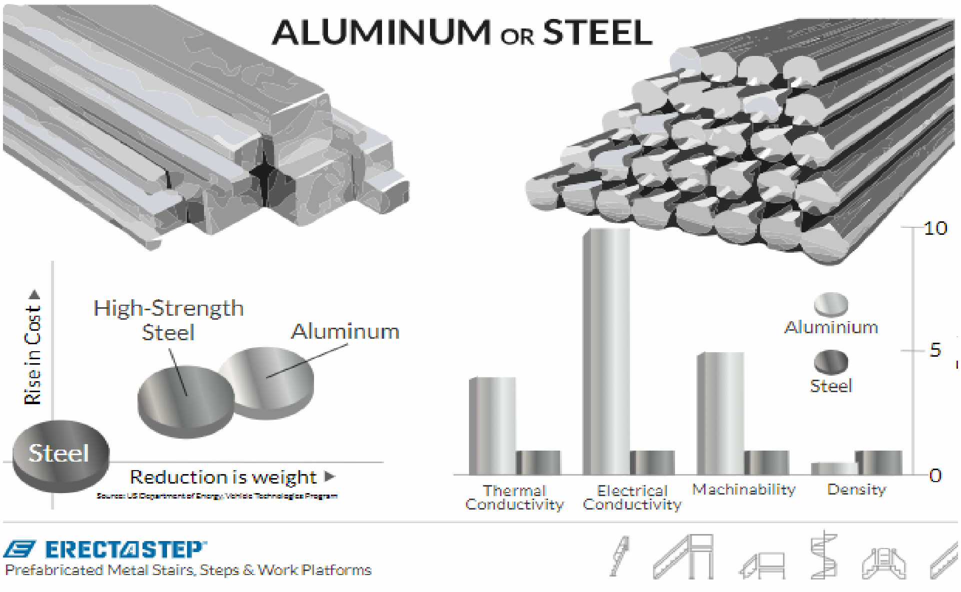


Figure 15. A comparison between aluminium and carbon steel (Erectastep, 2020)

3.1.2 Fundamentals of linear motion control

Linear motion is one-dimensional motion in a straight line (H.Nichols, 2018). Engineering advances in linear motion have developed a variety of options for driven actuator frameworks. The technology has a wide range of choices and among them, there are some essential mechanisms, which contribute hugely to the transformation of modern linear motion such as belt drive, chain drive, lead screw, ball screw, linear motor and roller pinion systems.

However, when deciding between these types of mechanisms, many vital criteria need to be considered. Some of the main factors include orientation, load, stroke length, speed, accuracy, and endurance under environmental conditions. Accuracy can be broken down into precision and repeatability. Precision measures how precise the assembly can move the load to the desired endpoint within a tiny tolerance. On the other hand, repeatability is a measure of the degree to which a driven cluster can continuously move a load to the same position. Moreover, expenses are also involved in the choice of the system's mechanism essentially.

Since the expenditure covers not only an up-front but also a long-term maintenance cost during the operation, a proper assessment should be done in order to pick the most suitable device for the application of the system (Lead Screw or Belt-Drives, n.d.)

Common types of linear structure:

a) Leadscrew uses a spiral structure of the thread to transform motion into linear motion. However, because of a huge-contacted area between the shaft’s thread and the nut, a great amount of frictional losses is created. Therefore, leadscrew is less efficient and accurate compared to the ball screw. Leadscrew has comparatively high load-bearing power. Although the load-bearing is less than the ball screw, one of the primary advantages of the leadscrew is the pricing, the cost is usually just one-tenth of its relative cousin – ball screw (Kliber, 2015).

Figure 16. Leadscrew (ABSSAC, n.d.)

b) Ball screw structure consists of a screw shaft and ball nut with recirculating bearings achieved by using a return tube (shown in Figure 17). The load is distributed by the rolling elements; hence the friction is reduced, high load volume increases. Moreover, due to the low level of friction, accuracy can be achieved in the ball screw. However, ball screw appears to be pricey, and frequent lubricating is required to maintain its condition. Finally, ball screw is susceptible to noise caused by recirculating balls (Kliber, 2015).

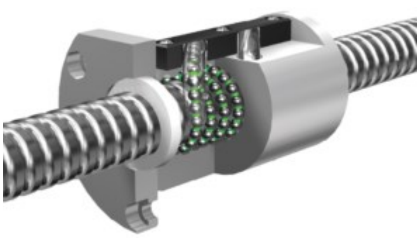


Figure 17. Structure of the Ball screw (Medical Design and Outsourcing, 2016)

c) A belt drive is typically selected due to its high speed, long stroke length, lower noise and relatively little maintenance. However, the accuracy and load capacity of the belt drive are not as high as with the lead/ball screw. Besides, stiffness and stretch are additional drawbacks (Kliber, 2015).

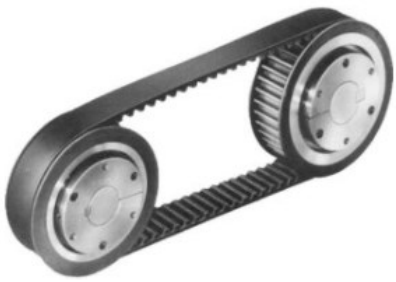


Figure 18. Belt drive (Collins, Pulley balancing for belt drives, 2017)

d) A chain drive, (illustrated in Figure 19), conveys rotary movement into linear movement by a roller chain (known as chain links) meshes a sprocket gear. Due to the metal material, chain drive is capable of working in difficult environments and is not easily damaged by sunlight or erosion. Nevertheless, chain type produces more noise and flutter than the belt drive (Kliber, 2015).

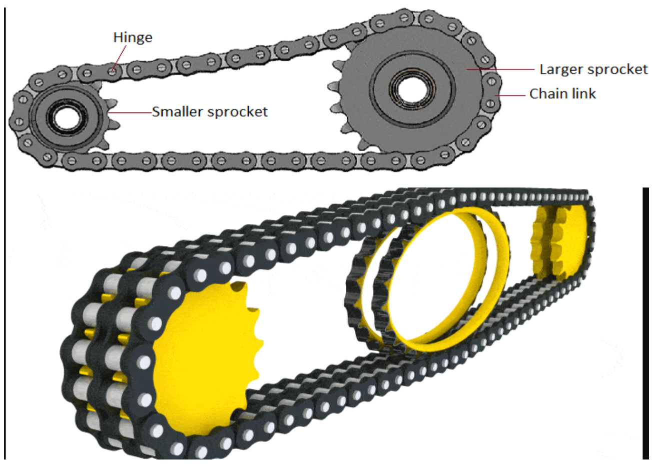


Figure 19. Chain drive (Mecholic, n.d.)

e) A rack gear and pinion (as illustrated in Figure 20), is a comprised set, in which a circular gear (also known as a pinion) engages a linear gear (a rack) to convey rotational motion into linear motion. Rack delivers smoother running at high speed and a great load volume thanks to the greater contact ratio of the tooth. To ensure proper operation, lubricating is a must. Since rack and pinion sets have comparatively few parts, they help to save time during assembly and improve reliability.

A high degree of precision is acquired even over long journeys (Kliber, 2015).

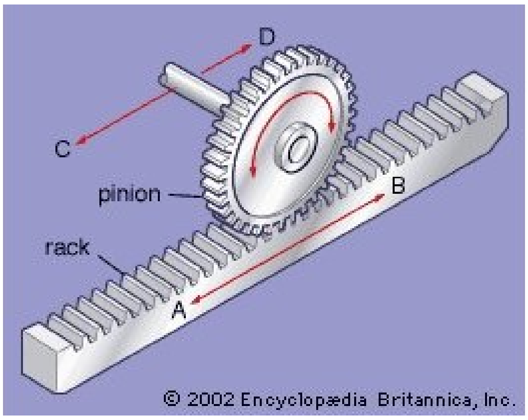


Figure 20. Rack gear and pinion set (Encyclopaedia Britannica, n.d.)

3.1.3 Leadscrew

Leadscrew was selected for the project due to the high accuracy and positional repeatability in linear motion. Moreover, leadscrew has competitive pricing and lower maintenance cost, compared to other types of linear motion structure. It is also preferred for safety reasons. Thanks to the holding mechanism, crashing or shifting in vertical applications can be prevented if a power outage occurs. The screw terminology includes two related fundamental concepts of the outer structure: pitch and lead. Since in most of the common screws, pitch and lead are the same, which makes them look easily confused.

Pitch is the distance from the screw grooves of one thread to the other thread. Lead is the travel distance, which the nut can make on the axis of the screw per one full screw revolution. In single start screws, the pitch and the lead are equal. For multiple start screws, the lead is equal to the division of the pitch by the number of starts (Thomson, n.d.).

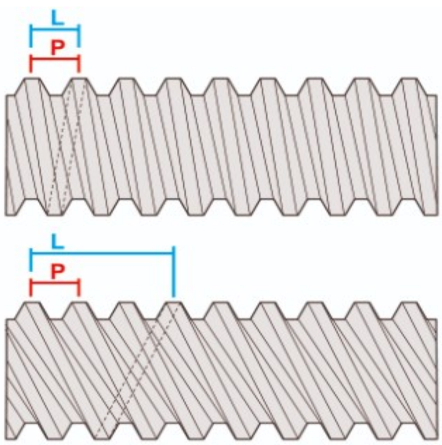


Figure 21. Pitch and lead on the screw (Thomson, n.d.)

Types of thread:

- Single-Start: With each revolution of the screw, the nut moves 2 mm. This gives higher resolution and torque, but with slower movement speed.

- Two-Start: Each revolution moves 4 mm. For many applications, it is a reasonable balance between speed and torque.

- Four-Start: Each revolution moves 8 mm. Fast movement is achieved, but at the cost of torque, the motor has to handle more. Furthermore, heavy load is likely to cause back-drive to the screw. The weight of the load, therefore, can lead to the screw's self-turning.

On the project, the single-start leadscrews were used for precision and high torque.

3.1.4 Linear guide

A linear guide is a set of traveling carriage that operates on a linear component called a rail (Lan, 2013, p. 18).

In order to obtain precise and repeatable linear motion, a linear axis must be steady enough to avoid deviation in undesired directions. Aside from a linear actuator to produce linear motion, the steadiness can only be achieved by comprising the system with the linear guide to confine the motion to a straight line.

There are several types of linear guide categorized by their characteristics and applications.

a) Plain linear slide which usually comes in two types: boxway and dovetail. Generally, plain slide has a high load capacity and is commonly used in stamping works and machine tools. However, sliding structure of the plain linear slide produces high friction which makes it a poor option for automation (Collins, 2018).

Figure 22. Plain linear slide (Collins, 2018)

b) The Linear Bush is a ball-based linear guide, which is used in combination with a cylindrical axis. This system offers linear movements with a low frictional resistance to ensure precise and fast operation (THK, n.d.).

Figure 23. Linear bush (THK, n.d.)

c) Flat Roller is a basic linear guide consists of a number of precision rollers retained by a pressed steel plate. This product is suited for large machines that require high rigidity with a minimal friction coefficient and an easy installation (THK, n.d.).

Figure 24. Flat roller (Ikont, n.d.)

d) The Cross-Roller Table is a lightweight, high-stiffness, high-precision, limited travel linear guide unit with integrated cross roller guides. This architecture offers a simple installation and a high accuracy linear guiding system.

Figure 25. Cross roller table (Misumi, n.d.)

The linear bush type was chosen for the linear guide structure due to the efficiency and accuracy it provides at a relatively low cost. The twin linear bush guide when properly constructed gives a comfortably smooth motion and a high load capacity. Moreover, linear bushes are readily available components.

Figure 26. Linear bush set (Amazon, n.d.)

3.2 **Electrical section**

The following chapter covers fundamental knowledge of electrical equipment. Chapter 3.2.1 and 3.2.2 present the instruction guide and basic concept of micro-stepping control. The transistor theory is later described in chapter 3.2.3. Limit switch and emergency stop are mentioned in chapter 3.2.4 and 3.2.5. Whereas in chapter 3.2.6, wire selection is listed out. Finally, rudimental understanding and the choice of the miniature circuit breaker are presented in chapter 3.2.7.

3.2.1 Micro stepper driver

In theory, a stepper motor can be directly driven by the controller. However, in reality, the controller's output current and voltage are either too small or too large to drive a stepper motor. PLC controller is only capable of outputting current with small amperes. Meanwhile, to move the stepper motor, a broad current range from 0.5A to 4 A is required. Therefore, we need an additional tool that fulfills the needs of sufficient operation.

The Micro stepping Driver TB6600 (shown in Figure 27), which is a specialized module for controlling bipolar two-phase stepper motors, is built around the TB67S109AFTG Toshiba controller chip (Bakker, 2018). The driver has the ability to control the mode of full step, half step, micro-step (1/4, 1/8, 1/16, and 1/32 step), which can be set on the hardware of the module. With a running current of 0.5 – 4 A, this driver module is an ideal option for stepper motors, e.g., NEMA13, NEMA17, etc. The driver is equipped with built-in safety functions, such as overheating, over current, under-voltage shutdown protection.

Figure 27. TB6600 stepper motor driver

The TB6600 module uses a 9-42 VDC power supply for the stepper motor operation; 36VDC is recommended (Bakker, 2018).

Table 1. Specification TB6600 (DFRobot, n.d.)

Input Current	0~5.0A
Output Current	0.5-4.0A
Power (MAX)	160W
Micro Step	1, 2/A, 2/B, 4, 8, 16, 32
Temperature	-10 ~ 45℃
Humidity	No Condensation
Weight	0.2 kg
Dimension	96*56*33 mm

The motor driver comprises several blocks:

a) Motor Driver Block uses IC TB67S109AFTG to control the operation of the stepper motor.

b) Optical isolation block isolates the control signal from the engine driver block.

c) Control signal block includes 6 pins:
   - ENA-, ENA+: Signal enables/disables the module to operate.
   - DIR-, DIR +: Signal controls the rotational direction of the motor.
   - PUL-, PUL+: Pulse signal controls the motor rotation.

   With a 2-pin design to control functions, the TB6600 module allows the user to select either a common-cathode or a common-anode wiring circuit. 5V control system can be directly connected to the control pin of the stepper driver. However, if the power supply exceeds +5V, a limiting-current resistor must be added. This will ensure the control system pin can output 8-15mA to operate the internal chip efficiently.

   Common-anode wiring (Figure 28) is done by connecting the pins ENA+, DIR+, PUL+ to the controller 5 VDC. The pins ENA-, DIR-, PUL- are connected to the controller's output terminals.

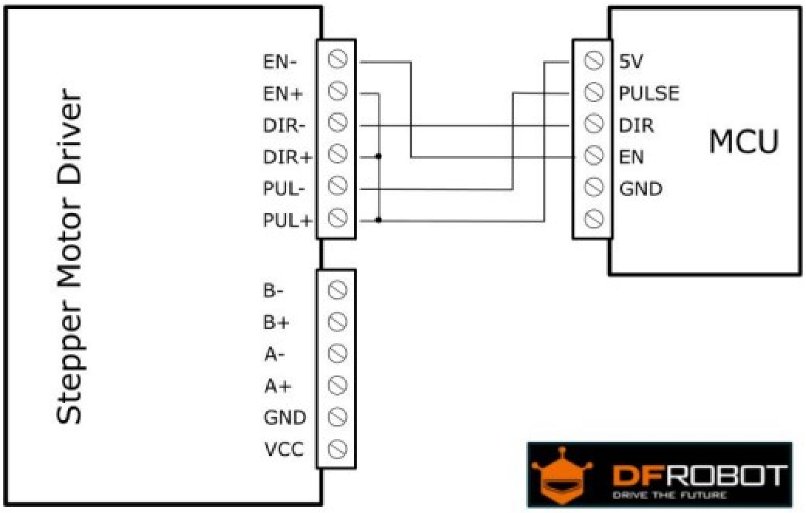


Figure 28. Common-anode connection (DFRobot, n.d.)

Common-cathode wiring as seen in Figure 29 is done by connecting the pins ENA-, DIR-, PUL- to the controller's ground terminal, the pins ENA+, DIR+, PUL+ are connected to the controller's output terminals.

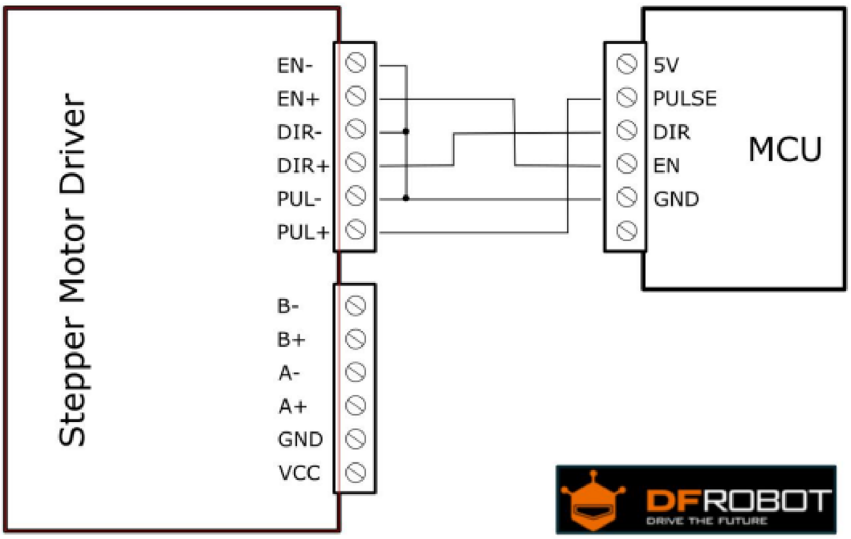


Figure 29. Common cathode connection (DFRobot, n.d.)

d) Motor Winding Block includes four pins: A +, A-, B +, B- allowing a connection of the bipolar stepper motor and four ends.

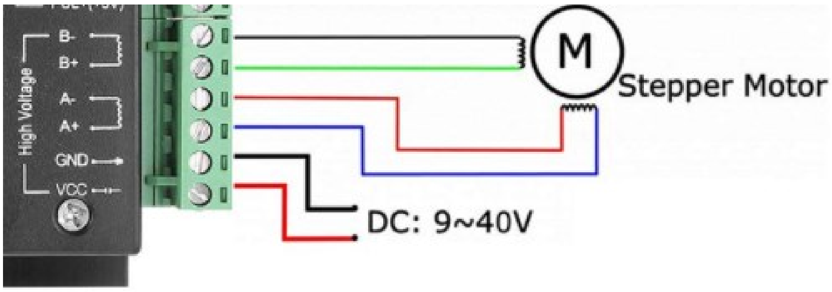


Figure 30. Power supply and motor winding connections

e) Mode setting block includes switches that allow users to select the optional modes of adjusting current and step width. Current selection adjusts the current output to the stepper motor (shown in Table 2)

Table 2. TB6600 Current setting (DFRobot, n.d.)

Current(A)	Peak current	S4	S5	S6
0.5	0.7	ON	ON	ON
1.0	1.2	ON	OFF	ON
1.5	1.7	ON	ON	OFF
2.0	2.2	ON	OFF	OFF
2.5	2.7	OFF	ON	ON
2.8	2.9	OFF	OFF	ON
3.0	3.2	OFF	ON	OFF
3.5	4.0	OFF	OFF	OFF

Micro-step selection (shown in Table 3) sets micro-steps for the driver circuit. For example, if the motor is 1.8-degree type, then an input one pulse will cause the motor to rotate 1.8 degrees, 200 pulses will turn the motor one revolution. With micro-step of 1/2, 1/8, 1/16; one pulse will respectively spin the motor 1/2, 1/8, 1/16 of 1.8 degrees. In general, the smaller excitation (micro-step) mode is, the quieter and smoother operation is achieved.

Table 3. TB6600 Micro step setting (DFRobot, n.d.)

Micro step	Pulse/rev	S1	S2	S3
NC	NC	ON	ON	ON
1	200	ON	ON	OFF
2/A	400	ON	OFF	ON
2/B	400	OFF	ON	ON
4	800	ON	OFF	OFF
8	1600	OFF	ON	OFF
16	3200	OFF	OFF	ON
32	6400	OFF	OFF	OFF

3.2.2 Stepper motor

A stepper motor is a brushless synchronous DC motor, which translates pulse's changes into a precise discrete angle ('step').

A stepper motor is classified into three main types (NJR, n.d., p. 1) :

Permanent-magnet stepper motor (PMS): Unlike other stepper motor types, the rotor of the permanent-magnet stepper is not toothed and is made of a permanent magnet. When the motor stator coils are connected to the DC power supply, a magnetic field with north and south poles can be interchanged by sequentially switching the current flow (NJR, n.d., p. 2). Accordingly, this rotating magnetic field from the stator forces the rotor's permanent magnet to spin by a certain angle to align with the stator's pole. Permanent-magnet stepper has high torque and also large step angle.

Variable reluctance motor (VRM): The rotor is made of plain soft iron, and the stator has more teeth than the rotor. The stator coils are energized in sequence so that only one pair of rotor teeth is aligned to the stator at a time. The motor operates based on the occurrence of minimum reluctance with the minimum gap. As a result, the rotor points will be attracted towards the stator magnet poles (Cameron, 1990, pp. 17-18). The disadvantage is the lack of a permanent magnet, thus having a negative effect on the torque.

Hybrid type (HSM) has combined aspects from the variable reluctance stepper motor and the permanent magnet stepper motor. The hybrid stepper motor has a magnetized rotor with toothed steel cup enclosures made of soft iron. Hence, one end of the rotor becomes the south pole, and the other end becomes the north pole. The teeth on two cups are aligned a specific degree with each other. When the stator is energized, the rotor teeth move and line up with the teeth of the stator. Each of these moves is ¼ of the rotor tooth (for a 2-phases stator) (Acamley, 2002). Since the common hybrid rotor has 50 teeth, the motor makes 200 steps per revolution. Therefore, the length of each step can be simply calculated by the number of rotor teeth:

$$Step\ angle = \frac{360}{4 \times 50} = 1.8° \qquad (1)$$

"The step length can be simply expressed in terms of the numbers of phases and rotor teeth" (Acamley, 2002, p. 8).

$$Step\ angle = \frac{360}{2\ \times stator\ phases\ \times rotor\ pole\ pairs} \qquad (2)$$

(Collins, 2018)

For instance, the hybrid stepper (2 phase stator) which has 18 rotor teeth, has a step angle of 5°. Meanwhile, a hybrid stepper motor (5 phase stator) produces 0.72° with 50 rotor teeth.

According to a survey conducted by Harris, Andjargholi, Lawrenson, Hughes, & Ertan, (1977, p. 1222), with the same given motor volume, a hybrid stepper produces a larger torque and a smaller step than the variable-reluctance motor.

Bipolar and Unipolar stepper motor comparison:

Table 4. Comparison between Bipolar and Unipolar stepper motor (NPM, n.d.)

Bipolar stepper	Unipolar stepper
Two leads per phase. For the conventional two-phase motor, there are 4 wiring leads	Three leads per phase. For the conventional two-phase motor, there are 5-6 wiring leads.
Voltage reversal is needed in order to change the direction	No voltage reversal
Higher torque as bipolar uses full coil	Lower torque as unipolar uses only half of the coil
Since the bipolar is designed with a single winding per phase, the current needs to fully decay before reversing. As the result, bipolar stepper has a slower speed compared to unipolar	For each winding, the current flows in one direction. Thereby, fully current decay is not required which results in a faster speed
Requires more advanced controller circuit	Unipolar can be simply controlled by 4 transistors

A unipolar stepper motor with 6-8 wiring leads can be considered as a “universal” motor which can be used flexibly as either a bipolar or a unipolar motor, depends on how the motor is wired (Electronics Stack Exchange, 2012).

- 4-wire: Bipolar only
- 5-wire: Unipolar only
- 6-wire: either Unipolar or Bipolar
- 8-wire: either Unipolar or Bipolar

For a motor with 6 leads, if the center leads of each coil are connected together, it becomes a unipolar motor. Whereas, to use the stepper in bipolar mode, the center leads must not be connected so that the coils only use their two end leads.

Stepper motors come in many types of shape, volume and variety of configurations and to properly use the stepper motor, wiring connection must be taken into account. Therefore, to figure out the wiring connection, there are several methods to determine the leads' position on the coil (Buildbotics, 2019):

- Find the manual document of the stepper motor. A good datasheet gives you everything you need to know about the specifications of the component, from the voltage-current ratings to the arrangement of the leads.

- Use the ohm meter as a tool to identify the coil leads. Any leads that showed to have a resistance between each other are parts of the same coil. Leads measured without resistance are parts of the different coils. The resistance between two ends of the same coil is twice the resistance between the end lead and the center lead. After the coil leads have been determined, one end of the coil can be connected to "+"and the other end can be connected to "– ". The connection can be either backward or forward, if the motor spin in an unwanted direction, it can be simply fixed by reversing one of the wiring coils pairs.

As in Figure 31; the pins 1, 2, 3, 4, 5, 6 of the stepper motor were respectively marked with different colors: brown, white, orange, red, grey, yellow.

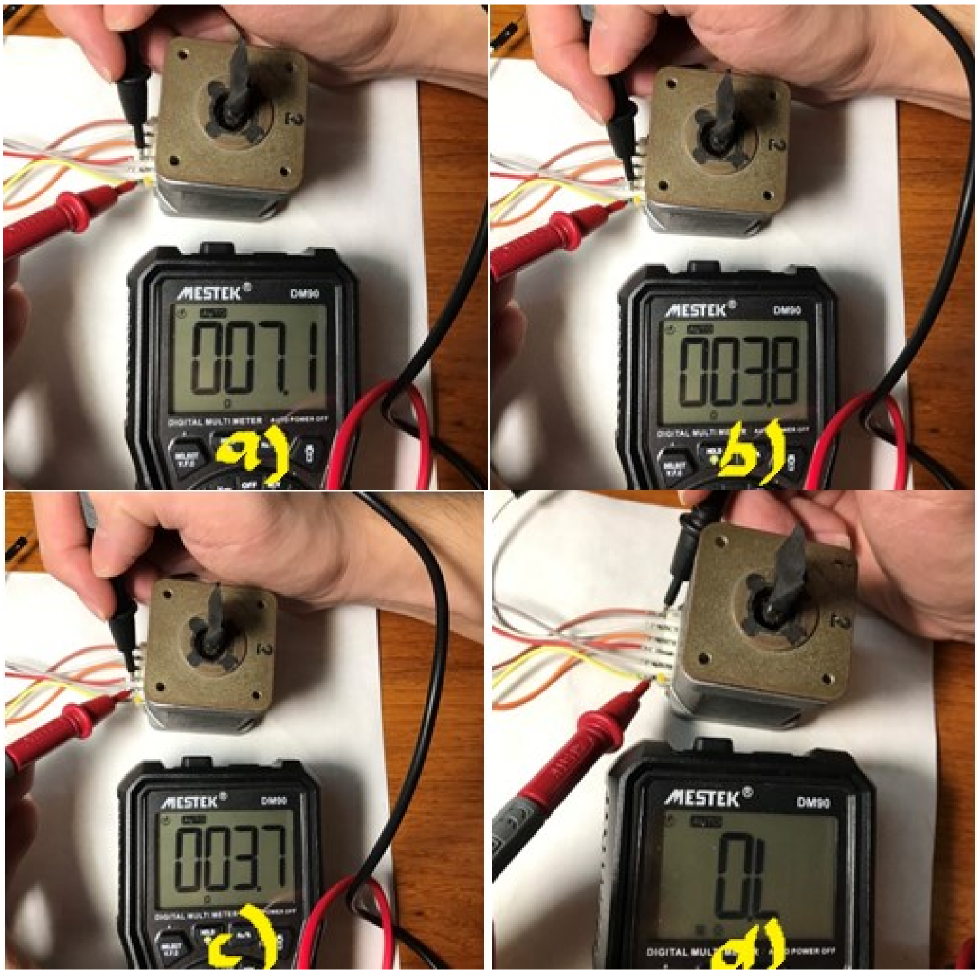


Figure 31. a) Resistance between pin 4 and 6, b) Resistance between pin 5 and 6, c) Resistance between pin 4 and 5, c) Resistance between pin 1 and 6

Table 5. Resistance measurement between each pin

	Brown	White	Orange	Red	Gray	Yellow
Brown		3.7 Ω	7.1 Ω	No value	No value	No value
White	3.7 Ω		3.8 Ω	No value	No value	No value
Orange	7.1 Ω	3.8 Ω		No value	No value	No value
Red	No value	No value	No value		3.7 Ω	7.1 Ω
Gray	No value	No value	No value	3.7 Ω		3.8 Ω
Yellow	No value	No value	No value	7.1 Ω	3.8 Ω	

According to the measurement from Table 5. White and Gray (2 and 5) are the center leads. Brown and Orange are two ends of the first coil. Red and Yellow are two ends of the second coil. Since the whole system requires high torque, bipolar wiring mode was chosen for the 6-wire hybrid unipolar stepper motor. These 6-wire steppers can be used either as a bipolar or a unipolar one.

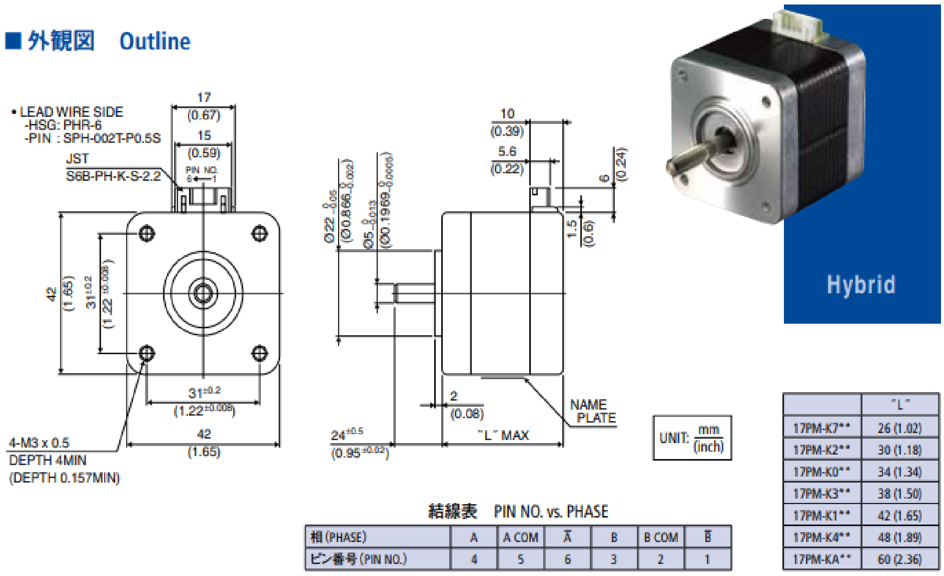


Figure 32. Stepper motor dimension (Eminebea, n.d.)

Table 6. List of stepper motors used for the project

Motor								
Axis	Manufacturer	Model	Step angle (deg.)	Drive sequence	Rated current (A)	Resistance (Ohms)	Holding torque (mNm)	Rotor Inertia (g.cm2)
Y X	Minebea	17PM-K442U	1.8	Uni-polar	1.4	2.8	400	75
Z T	Minebea	17PM-K342U	1.8	Uni-polar	1.4	2.0	250	50g

3.2.3 Transistor

A transistor which stands for Transfer Resistor according to (Wennrich, 2019, p. 396) is a small, solid component used for general purposes of amplifying power and switching applications. Nowadays, transistor is virtually packed in every electronic device. It comes in a wide range of styles and types, and each has its unique characteristics, but most of the transistors are composed of semiconducting properties: germanium or silicon. This semiconducting element is selectively doped with other properties, such as phosphorus, boron, arsenic or gallium, etc. Once the doping method implants impurity atoms in the semiconducting crystal, it results in either creating a defect in the structure of the material (P-type) or adding extra electrons on it (N-type) (Reisch, 2003, p. 6).

On the bipolar transistor, there are three terminals: Emitter, Base, Collector (shown in Figure 33 and Figure 34). The base terminal is used for controlling, while the emitter and collector are for negative and positive leads. Transistor can be either PNP Sourcing Type (N-type semiconductor is layered between 2 P-type layers) or NPN Sinking type (P-type semiconductor is layered between 2 N-type layers).

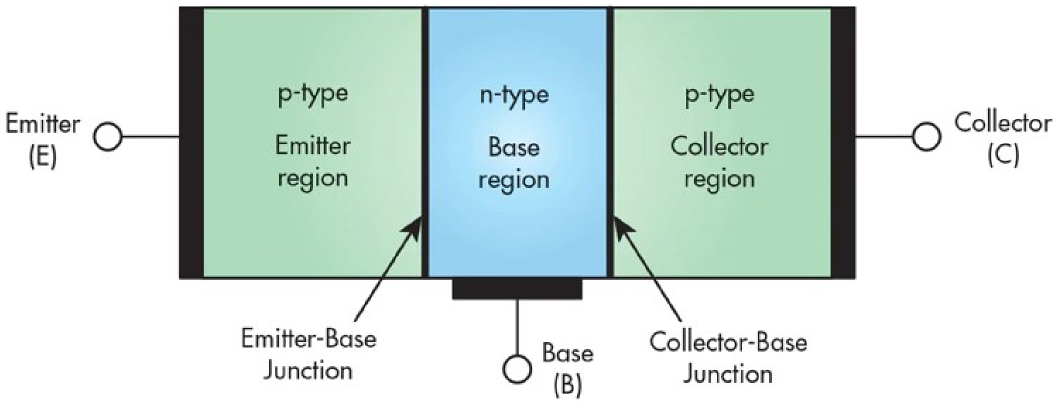


Figure 33. PNP transistor and its layered structure (WikiBooks, n.d.)

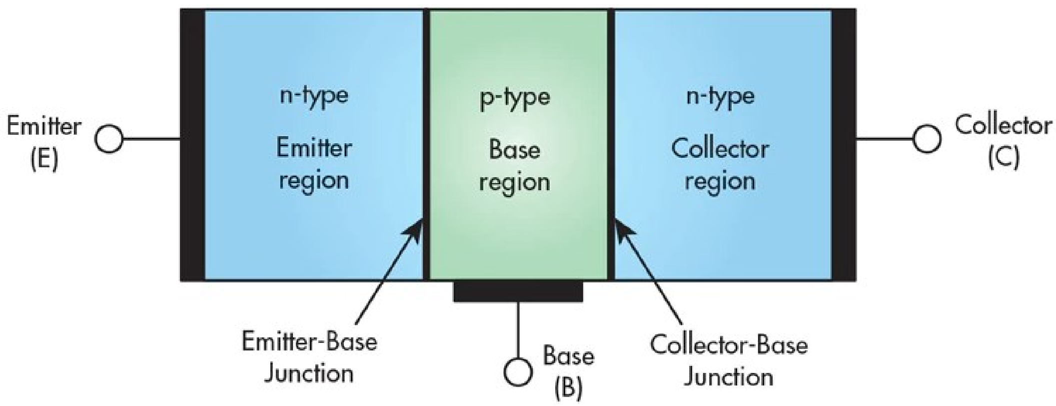


Figure 34. NPN type and its layered structure (WikiBooks, n.d.)

In NPN transistor, the positive lead is connected to the collector terminal, and current flows from the collector to the emitter. While in PNP transistor, the positive lead is connected to the emitter terminal so that the current flows from the emitter to the collector (described in Figure 35 and Figure 36).

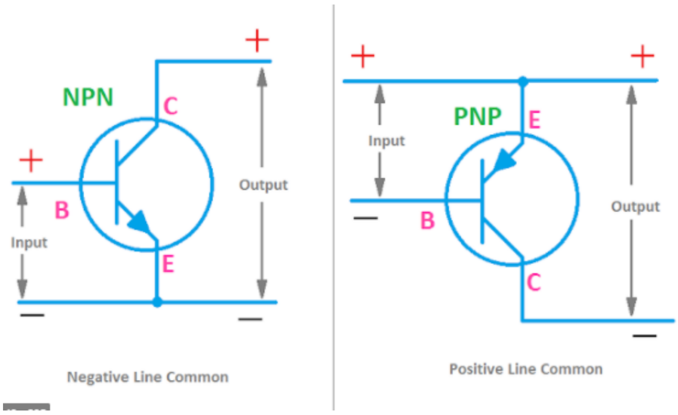


Figure 35. Wiring comparison between NPN and PNP (Pinterest, 2020)

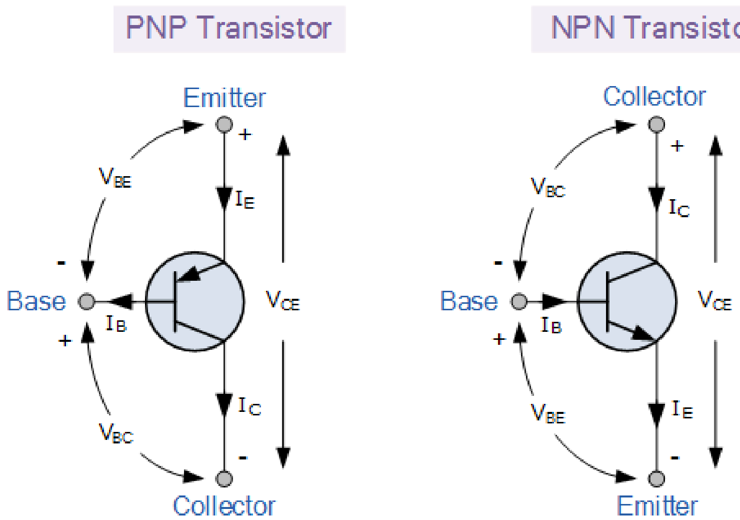


Figure 36. Pin layout between PNP and NPN transistor (Electronics Tutorials, n.d.)

Even though silicon transistor was invented later, it is now the most widely and commonly used compared to the germanium type. Due to the larger intrinsic density of germanium, a sudden temperature rise can lead to a considerable increase in reverse current. Meanwhile, with silicon properties, transistor can operate under a wider range of temperature, such as in switching applications. As a result, this contributes extensively to the advantages of silicon bipolar transistor (Reisch, 2003, p. 6).

Due to the versatility and the specialized feature for medium switching applications, the TIP41C Bipolar NPN Silicon transistor was selected for the project.

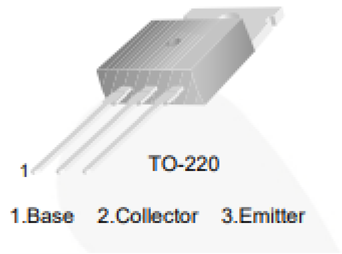


Figure 37. Pin layout of TIP41C (Onsemi, n.d.)

Specifications:

Table 7. Maximum ratings of TIP41C (Onsemi, n.d.)

Symbol	Parameter	Value
V_{CBO}	Collector-Base Voltage	100 V
V_{CEO}	Collector-Emitter Voltage	100 V
V_{EBO}	Emitter-Base Voltage	5 V
I_C	Collector Current (DC)	6 A
I_{CP}	Collector Current (Pulse)	10 A
I_B	Base Current	2 A
T_J	Junction Temperature	150 °C

Table 8. Electrical characteristics of TIP41C (Onsemi, n.d.)

Symbol	Parameter	Conditions	Min.	Max.	Unit
h_{FE}	DC Current Gain	V_{CE} = 4 V, I_c = 0.3 A	30		
		V_{CE} = 4 V, I_c = 3 A	15	75	
V_{CE} (sat)	Collector-Emitter Saturation Voltage	I_C = 6 A, I_B = 600 mA		1.5	V
V_{BE} (on)	Base-Emitter On voltage	V_{CE} = 4 V, I_C = 6 A		2.0	V
f_t	Current Gain Bandwidth Product	V_{CE} = 10 V, I_C = 500 mA, f = 1MHz	3.0		MHz

3.2.4 Proximity and limit switch

There are two types of 3-wire sensors available: PNP and NPN (described in Figure 38). The selection of sensors is determined by the controller circuit design. In some PLCs, the input can perform as either sourcing or sinking type. It is, therefore, essential to identify which wiring connection of PLC should be used. Generally, in Vietnam, the NPN sensor is preferable as PLC input is commonly used in sourcing type. Accordingly, an NPN normally-open proximity switch LEFIRCKO LJ12A3-4-Z/BX (shown in Figure 39) was chosen for the T-axis.

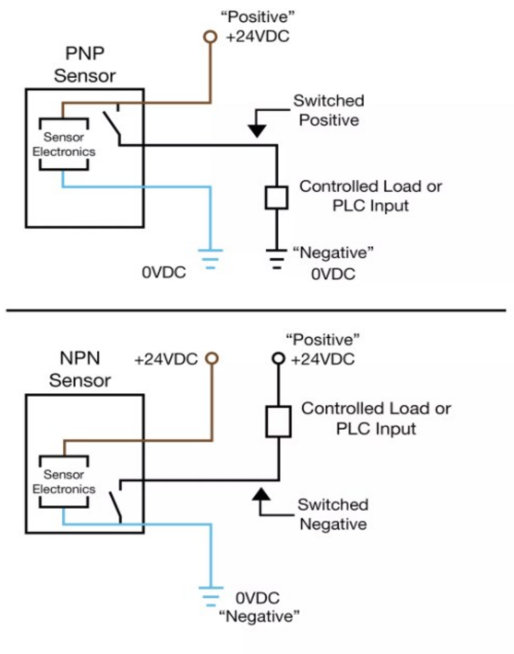


Figure 38. PNP vs NPN connection (Innovating Automation, n.d.)

Figure 39. LEFIRCKO LJ12A3-4-Z/BX (Opencircuitshop, n.d.)

For normal on/off-detecting function, limit switch LXW5-11G2 was selected.

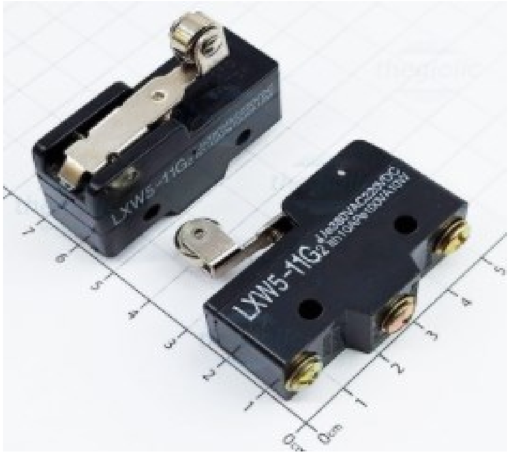


Figure 40. LXW5-11G2 limit switch (thegioiic, n.d.)

3.2.5 Emergency stop

LA38 (shown in Figure 41 and Figure 42) self-locking switch was selected as an emergency button. There are usually two types of connection on the emergency stop button: Normally-open and normally-closed. In terms of operating time, normally-closed contact responds faster than the normally-open contact due to the natural state of release. Secondly, in default status, normally-closed contact continuously sends signals to the control system. A fault in the wiring or pushing button action causes immediate disconnection in the circuit. However, on the other hand, in default status of normally-open contact, the control does not receive any signal until the button is pressed. A loose connection, therefore, can cause a fail emergency operation. In conclusion, a normally-closed connection is a correct way to wire the emergency push buttons and it was chosen for the project.

Figure 41. Emergency switch button LA38/203 209B (Aliexpress, n.d.)

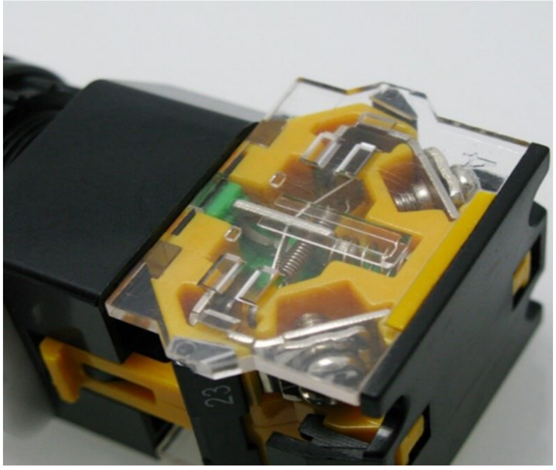


Figure 42. Normally open contacts of emergency stop (Aliexpress, n.d.)

3.2.6 Wire selection

Wire is commonly categorized into 2 types: solid wire and stranded wire. The solid type is made of a single piece of metal which gives the wire more strength but less flexibility than the stranded type. Therefore, the wire is likely to crack if subjected to frequent flexing. The stranded type, on the other hand, is composed of several small strands, which are clustered together (Omnicable, n.d.). Stranded wire is more flexible than solid wire which makes it a suitable choice for the project.

The wiring section was divided into two main lines. According to the manufacturer's datasheet (indicated in Figure 43), the decision was made as follows:

Power supply line:
24 Vdc; 2.5 A: PVC Insulated stranded wire VCm 0.5 mm
24 Vdc; 8.8 A: PVC Insulated stranded wire VCm 1 mm
220 Vac: PVC insulated stranded wire VCm 1.5 mm

Control line:
PVC Insulated stranded wire VCm 0.5 mm

Dây đôi mềm, ruột đồng *Flexible copper conductor – PVC insulated wire*			
Số lõi *Num. of core*	**Tiết diện** *Nom. area of conductor*	**Dây đôi mềm dẹt, mềm xoắn** *VCmd , VCmx*	**Dây đôi mềm tròn, mềm ovan, mềm oval dẹt** *VCmt , VCmo, VCmod*
	mm²	A	A
2	0,5	5	7
2	0,75	7	10
2	1,0	10	11
2	1,25	12	13
2	1,5	14	15
2	2,0	16	17
2	2,5	18	20
2	3,5	-	24
2	4,0	-	27
2	5,5	-	32
2	6,0	-	36

Figure 43. Current ratings of PVC wire (Cadivi-vn, n.d.)

3.2.7 Miniature circuit breaker

Miniature circuit breaker is an automatically protective device designed to avoid damages caused by the excess current from a short-circuit or an overload. It is categorized into different classes. Selecting a miniature circuit breaker, therefore, requires some attention.

Short circuit protection: According to Figure 44, The copper wire PVC insulated with a nominal diameter of 1.5mm^2 can withstand the permitted value of 29700 A^2.s. To what extent, miniature with the rated current below 16 is suitable for the project 220 VAC circuit. For example, the S201-B16 miniature circuit breaker limits the let-through energy to approx. 20000 A^2.s, which is far less than the let-through 1.5 mm^2 wire permit. Consequently, the wire can be protected when a short circuit takes place.

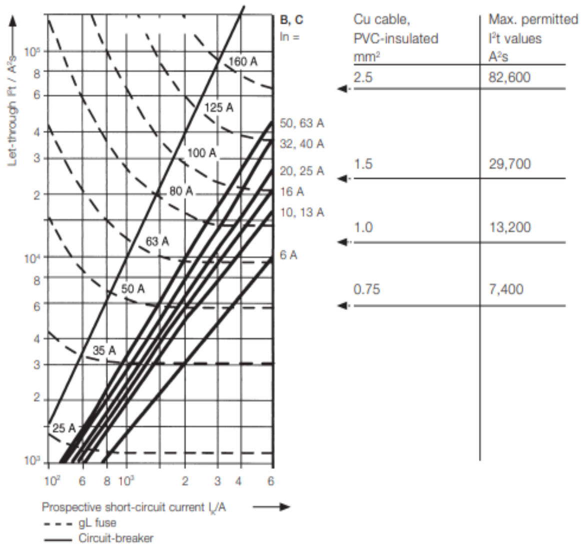


Figure 44. Let-through energy (ABB, 2013)

MCB characteristics: The miniature circuit breaker is also classified into different tripping characteristics for different purposes. Generally, when the switching power supply power is on, an instantaneously strong surge current in the circuit will occur, this inrush current can come up to over 10 times of normal input current and the period only takes place within several milliseconds. Therefore, the tripping characteristics must be selected carefully to avoid unintended tripping of the circuit breaker during the surge.

With B characteristic, from Figure 45, surge current between 3 to 5 times the rated current will trip the miniature MCB within a specified time. For instance, 3.1 times of the rated current does not trip before 2.1 seconds and the latest trip will occur after 40 seconds. The short circuit with a current of 5 times the rated current will trip the MCB immediately. The white curve represents the characteristic of a copper cable. As the curve lies in the safe tripping zone, cables will be protected.

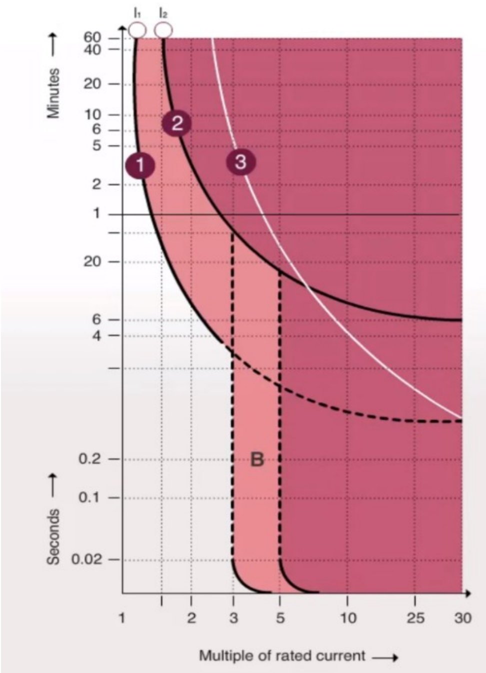


Figure 45. Protection level of B characteristic (ABB, 2013)

“K” and “Z” characteristics, according to Figure 46, provide better protection performance during the operation due to their tripping zone which draws close to the multiple of rated current “1” at the curve’s end. “Z” characteristic is sensitive as small peaks can trigger to trip the MCB, hence it is used to protect the semiconductors. “B”, ”C”, ”D” characteristics are commonly used for the protection of cables. Meanwhile, “K” is used for the protection of windings in transformers and motors.

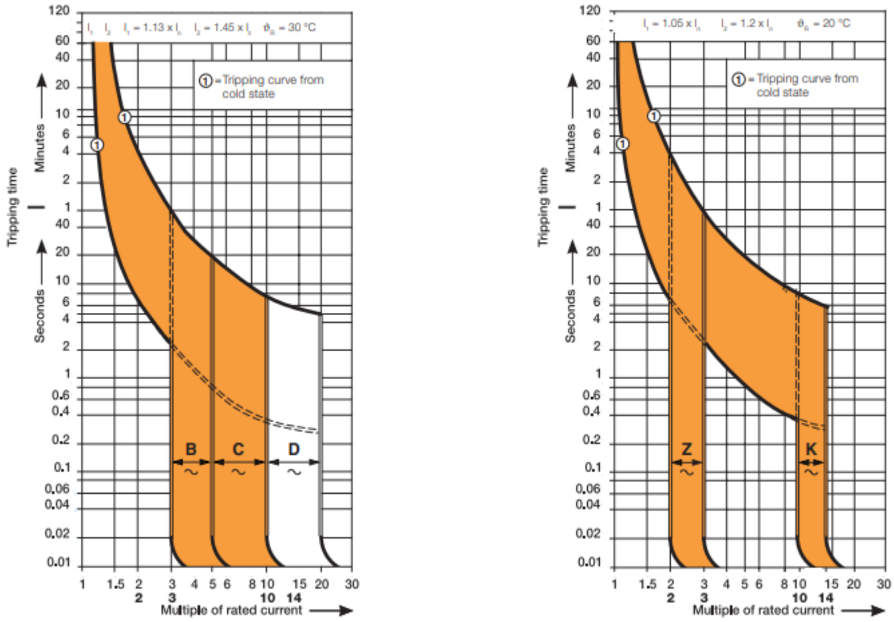


Figure 46. Comparison of protection level (ABB, 2013)

Base on the Siemens' datasheet (Siemens, 2020), the suggestion for plc S7 1200's Miniature Circuit Breaker is 16 A characteristic B or 10 A characteristic C. Therefore, the miniature circuit breaker ABB S201-B16 was selected (Figure 47), which was also compatible/qualified for the stepper motor's switching power supply (32 A inrush current).

Figure 47. Miniature circuit breaker S201-B16 (ABB, n.d.)

4 IMPLEMENTATION

The following chapter covers the design details and implementation of the AS/RS. First, the design of shelves and axis arrangement are presented in Chapters 4.1 and 4.2. Then, details of Y, X, Z, T axis implementation are described in Chapters 4.3, 4.4, 4.5 and 4.6, respectively. Lastly, the wiring structure and layout of equipment are illustrated in Chapters 4.7.

4.1 Design of shelves

Two vertical shelves (left shelf and right shelf) were placed distinctively on two opposite sides of the base, which left an aisle for the operation of the A/S machine (illustrated in Figure 48). To solve a space-saving problem, each shelf was designed with two floors. On each floor, there were 3 slots to store/retrieve the load, which made up a total of 12 slots. The same storing/retrieving place was located next to the right shelf.

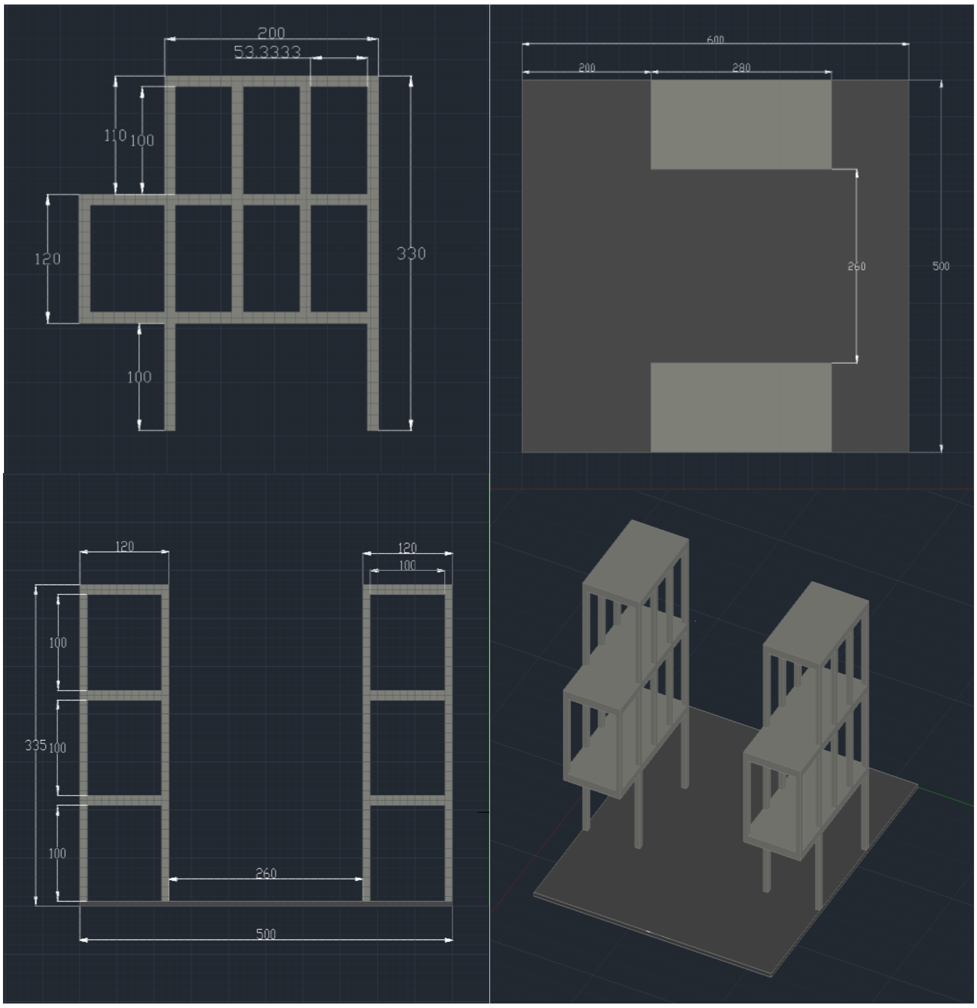


Figure 48. Structure and dimension of the shelves

4.2 Axis arrangement

This chapter illustrates the design movement of the AS/RS system. In order to design a system, which was able to transfer a load onto two separate shelves, the S/R machine structure was divided into four main axes. Firstly, the X-axis provided linear motion which helped to transfer/retrieve the load onto/out of the shelf. Secondly, the Y-axis provided linear motion which moved along the aisle. Then, the Z-axis provided linear motion which assisted in lifting the load up/down. Finally, the T-axis provided rotational motion which assisted in shifting the load back and forth between the right and left shelves. The initial design as shown in Figure 49 was to separate the structure into 2 parts: a lower body and an upper body of the S/R machine. The lower body consisted of Y and T, while the upper body consisted of Z and X.

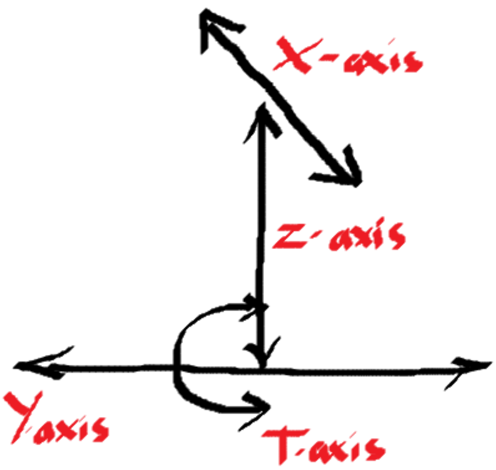


Figure 49. The first design of S/R hand’s movement

This design was taken into serious consideration. Since the lower body had to carry a more massive weight, the T axis was required to deliver a significant amount of torque to turn the whole machine from left to right, vice versa. A pneumatic 180-degree rotation actuator was deliberated as the broad range of torque it could produce. However, although the air pressure could be controlled to give the AS/RS machine a desired speed and torque, the complexity in installing the pneumatic actuator was a challenge for the project. Moreover, the pneumatic actuator was not an economical option and readily available component.

The second design (illustrated in Figure 50) was brought out to solve the installation difficulties and pricing issues. The solution was to use the X, Y for the lower body and Z, T for the S/R machine's upper body. As a result, T-axis was free from carrying heavyweight structure, and the whole system synchronously operated in the same screw-drive mechanism.

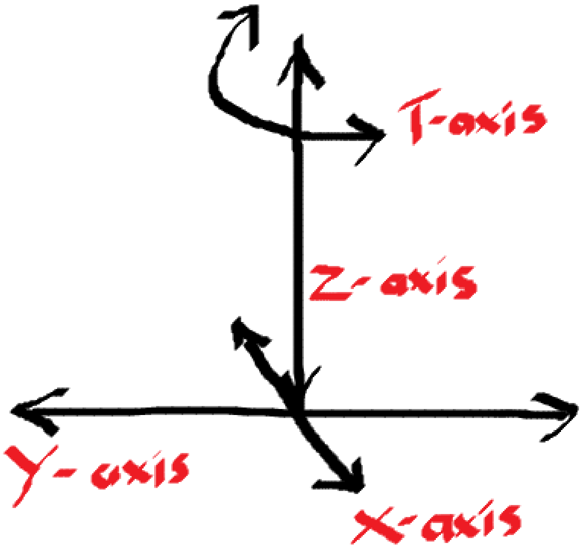


Figure 50. The final design of S/R hand's movement

4.3 Implementation of Y-axis

The Y-axis (shown in Figure 51) consisted of a 500x600 mm aluminium base platform, the main leadscrew system, and a linear optical guide axis. The linear guide was a set of a 600 mm steel optical rail with 8 mm in diameter steadily supported at two ends by two KP08 bearings. To securely guide the load to the desired direction, two ball-based linear bush SC8UU bearing were used. The main leadscrew was constructed with a T8 nut covered by a nut housing bracket, which travelled on a 500 mm T8 leadscrew. The leadscrew shaft was supported by two KP08 bearing brackets at each of its ends. Then, a 5x8 flexible coupling was attached to connect the leadscrew to the shaft of the motor.

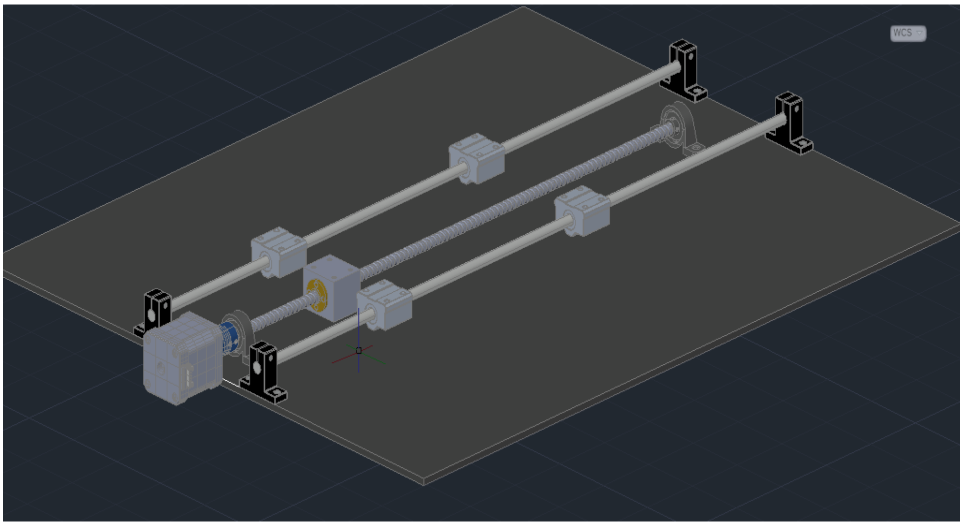


Figure 51. Structure of Y-axis

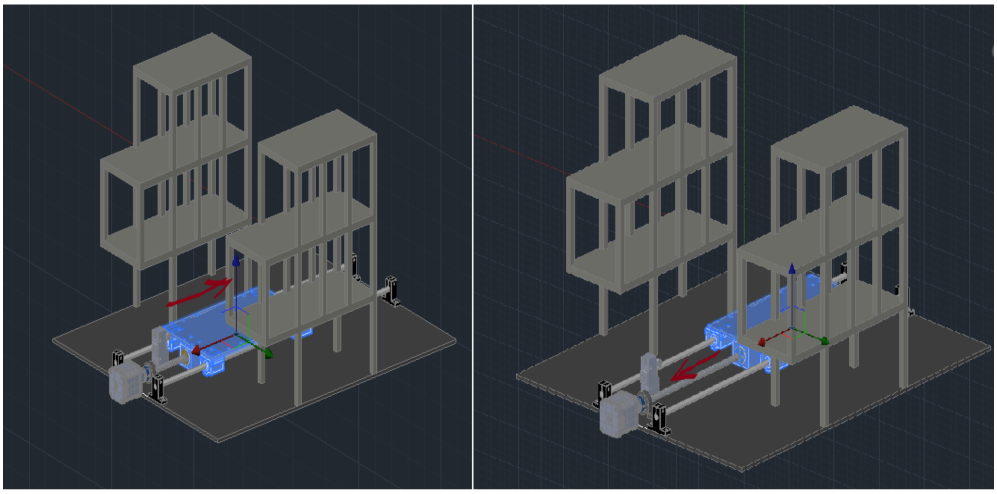


Figure 52. Side view of Y-axis' movement

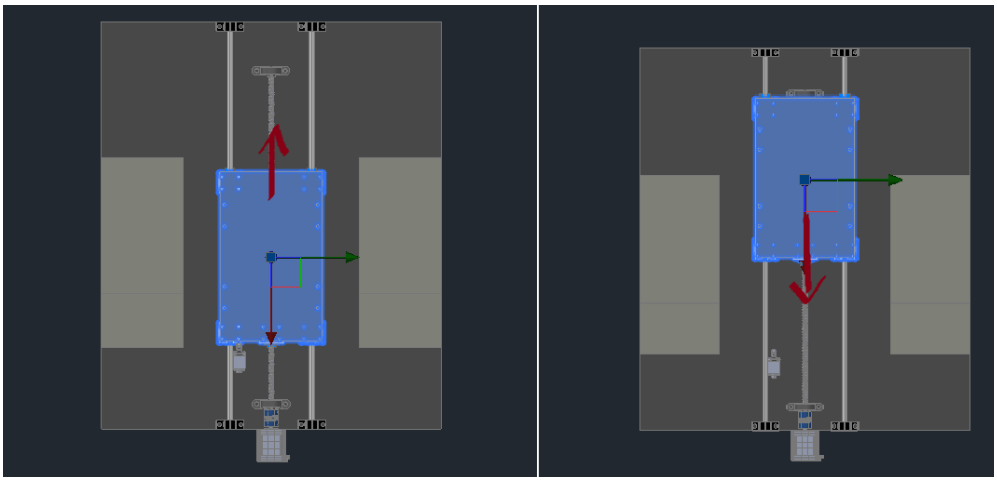


Figure 53. Top view of Y-axis' movement

4.4 Implementation of X-axis

Much like the Y-axis, the X-axis (illustrated in Figure 54) was made of a 150x250 mm aluminium base platform, the main leadscrew system, and a linear optical guide axis. The linear guide was a set of a 150 mm steel optical rail with 8 mm in diameter steadily supported at two ends by two KP08 bearings. To securely guide the load to the desired direction, two ball-based linear bush SC8UU bearing were used. The main leadscrew was constructed with a T8 nut covered by a nut housing bracket, which travelled on a 110 mm T8 leadscrew. The leadscrew shaft was supported by two KP08 bearing brackets at each of its ends. Then, a 5x8 flexible coupling was used to connect the leadscrew to the shaft of the motor.

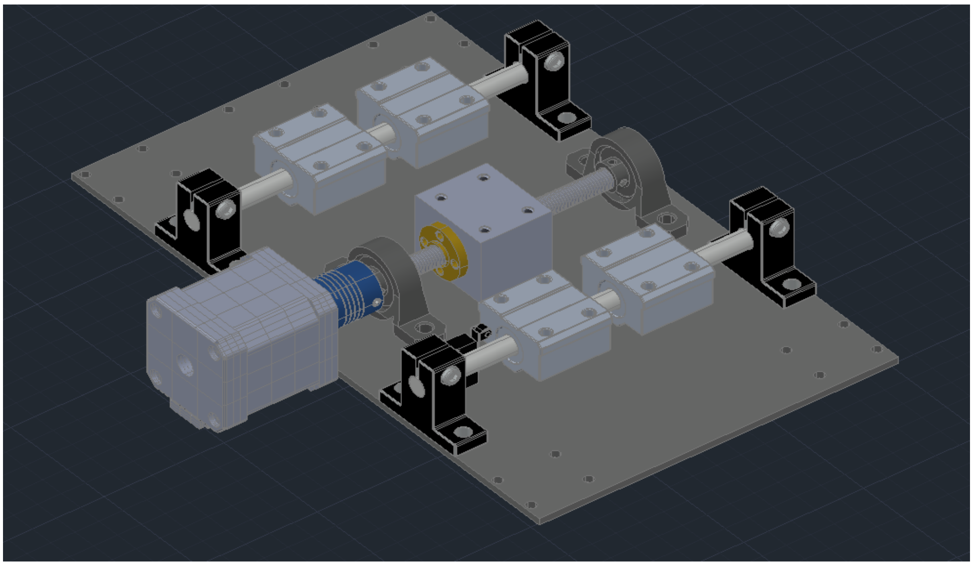


Figure 54. Structure of X-axis

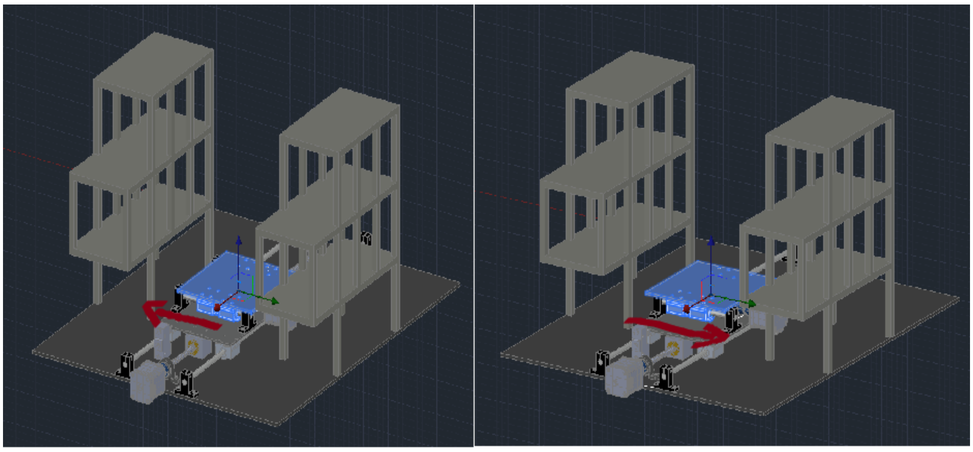


Figure 55. Side view of X-axis' movement

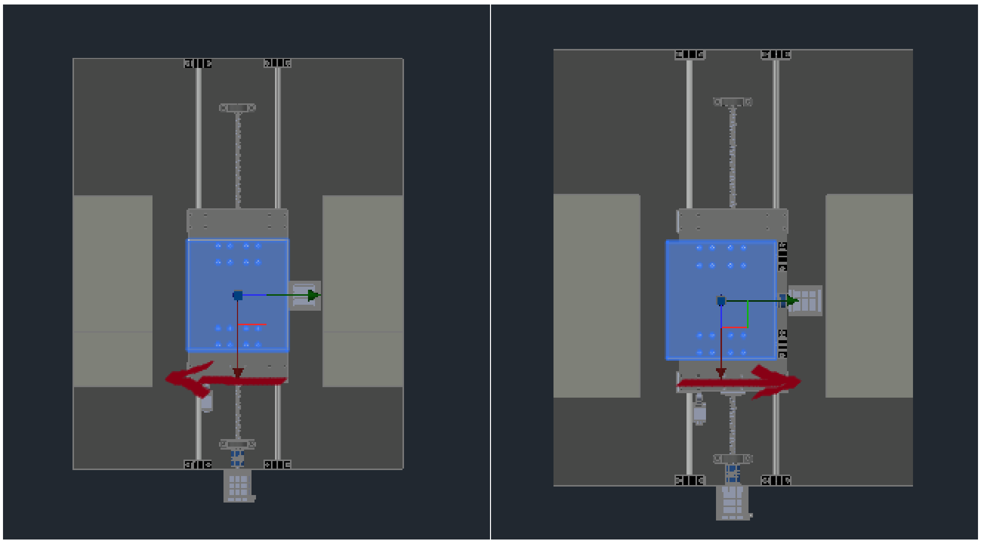


Figure 56. Top view of X-axis' movement

4.5 Implementation of Z-axis

The Z-axis (indicated in Figure 57) consisted of a 150x250 mm aluminium base platform, the main leadscrew system, and a linear guide system. A 250 mm 2040 v-slot aluminium extrusion (Figure 58) and four pieces of v-slot wheel type B with 625ZZ bearing (Figure 59) were selected for the linear guide system. To constrain main leadscrew movement to a desired straight line, v-slot wheels were screwed on to a 100x100 mm vertical aluminium base carrier to be able to travel along the v-slot extrusion rail. The main leadscrew was constructed of a T8 nut covered by a nut housing bracket, which travelled on a 200 mm T8 leadscrew. The head of the screw was mounted with a 5x8 rigid coupling. Additionally, to place a motor on top of the Z-axis, a 45x80 mm aluminium base was screwed on to the top of the v-slot extrusion frame.

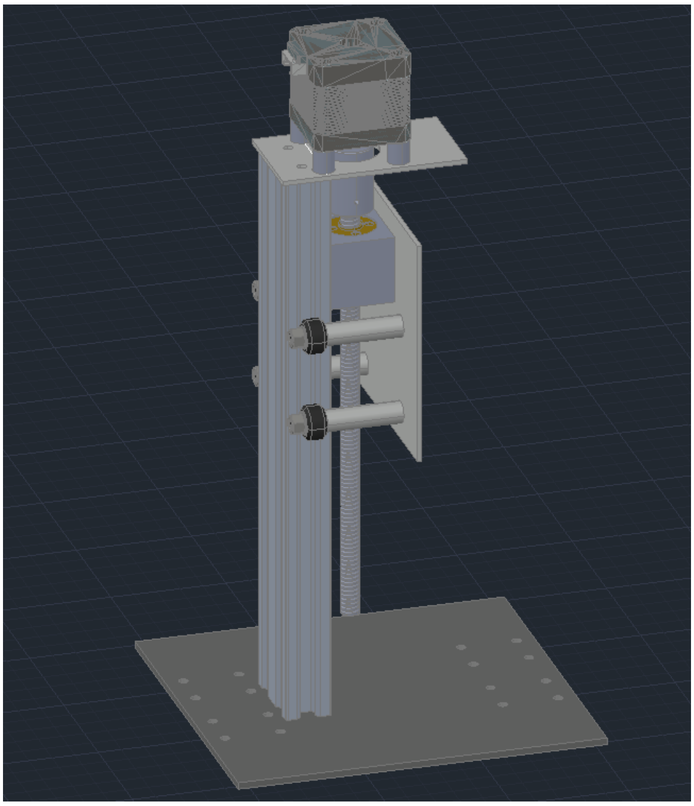


Figure 57. Structure of Z-axis

Figure 58. 2040 V-slot aluminium extrusion (Banggood, n.d.)

Figure 59. V-slot wheel types with bearings (AliExpress, n.d.)

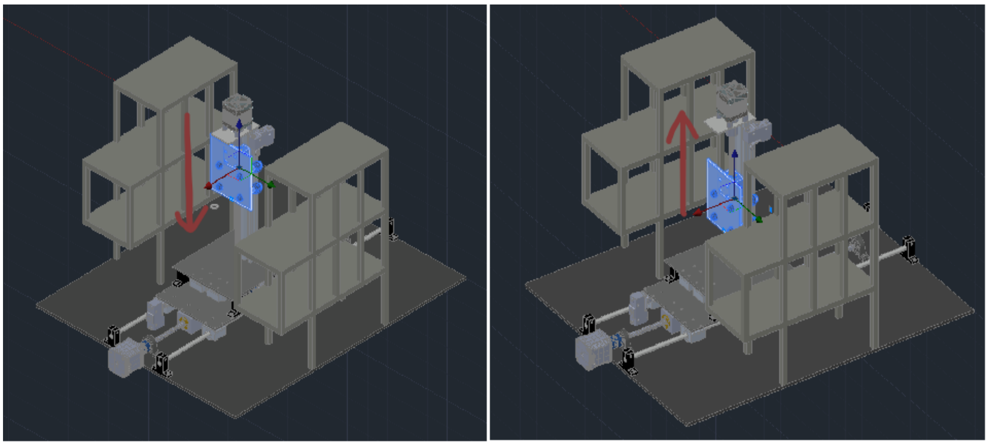


Figure 60. Side view of Z-axis' movement

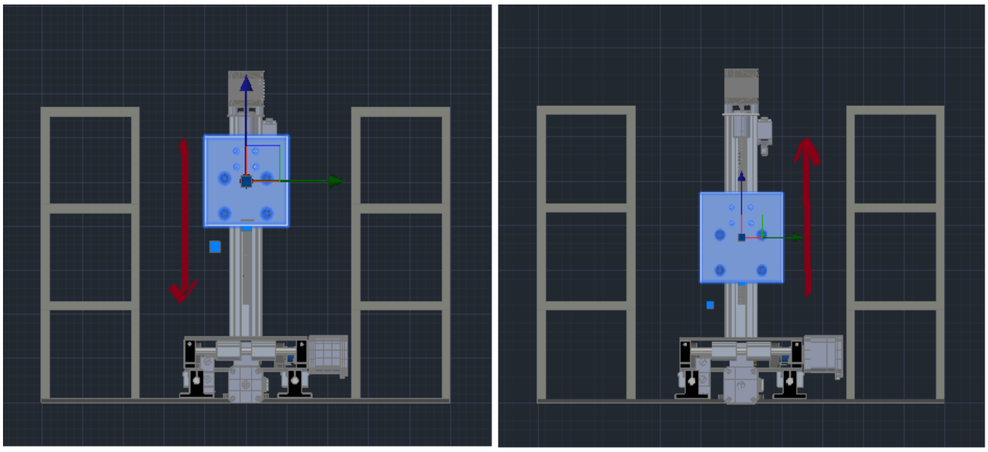


Figure 61. Front view of Z-axis' movement

4.6 Implementation of T-axis

The T-axis (shown in Figure 62) consists of a 100x100 mm aluminium base, two 80 mm 2020 v-slot aluminium extrusions (Figure 63), a main rotational screw system and a dark mica-reinforced forklift. A motor was placed on top of the aluminium base. On both sides, v-slot extrusions were used for the T-left and T-right sensors’ attaching. The main rotational screw system was assembled from a 60mm M8 Hex bolt screw with a 5x8 rigid coupling mounted at its end. To ensure the stiffness of the fork, nuts and flat washers were added to the forklift to fasten it into a fixed position.

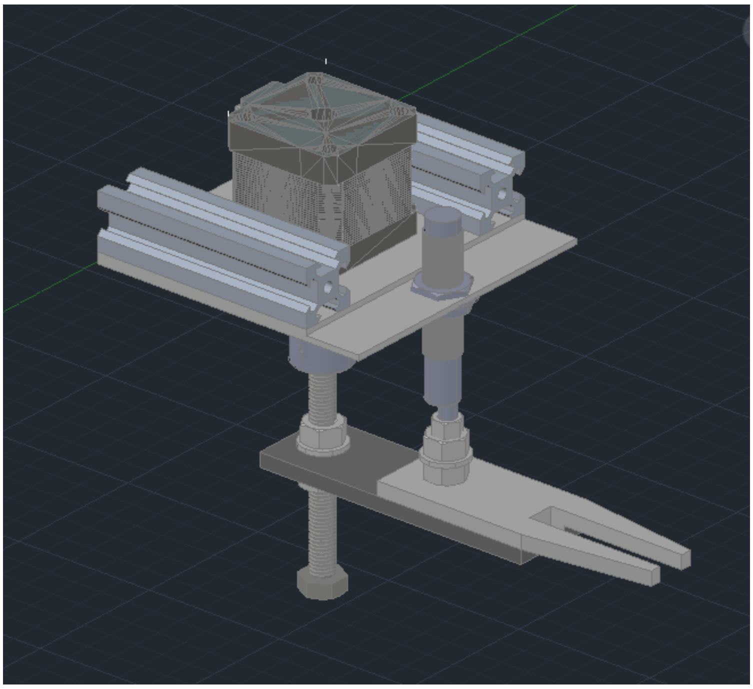


Figure 62. Structure of T-axis

Figure 63. 2020 V-slot aluminium extrusion (Makeralot, n.d.)

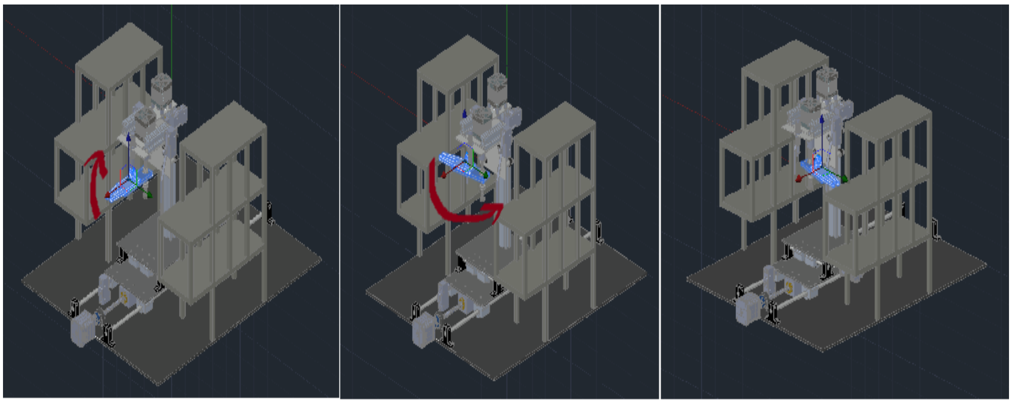


Figure 64. Side view of T-axis' movement

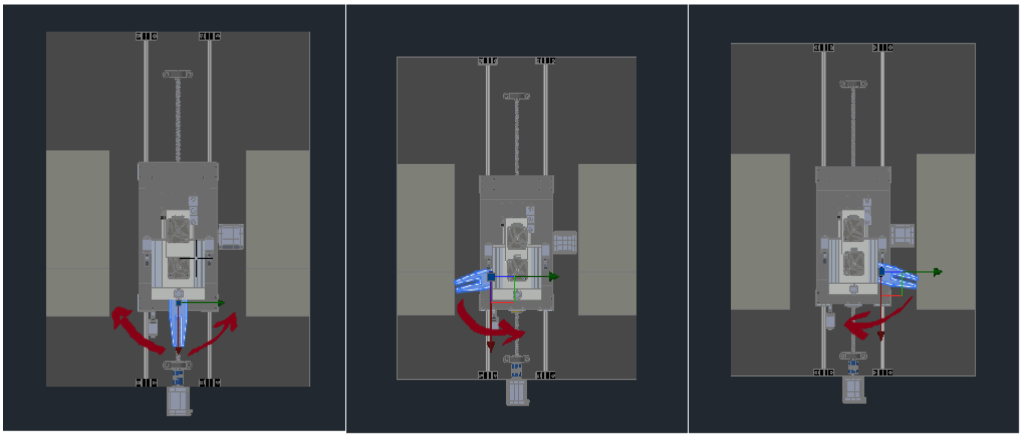


Figure 65. Top view of T-axis' movement

4.7 Wiring diagram and layout of equipment

4.7.1 Power supply wiring diagram

The power supply was divided into two units (shown in Figure 66). The first unit T1 was the SIMATIC Power Module PM1207 specialized for the usage of PLC S7 1200. This module can output 24VDC with a rated current value of 2.5 A.

The second unit T2 was used for stepper drivers. The output current of the power supply was taken into consideration. The power supply must meet the need of total current consumption to ensure the components work properly and efficiently. Since there were four stepper motor drivers connected in parallel and each of the drivers required 0-5 A, the output current needed can be calculated as an equation below:

$$I_{Required} \leq I_1 + I_2 + I_3 + I_4 = 5 + 5 + 5 + 5 = 20A \qquad (3)$$

The current required must be less than or equal to 20 A. Moreover, as each of the stepper drivers only needed 2 A, a suitable output current for the power supply was calculated as followed:

$$I_{Sum} \approx I_1 + I_2 + I_3 + I_4 \approx 2 + 2 + 2 + 2 \approx 8\ A \quad (4)$$

Therefore, the switching power supply 200 W-24 VDC-8.8 A was chosen, which provided an adequate current of 2.2 A to each of the motor drivers.

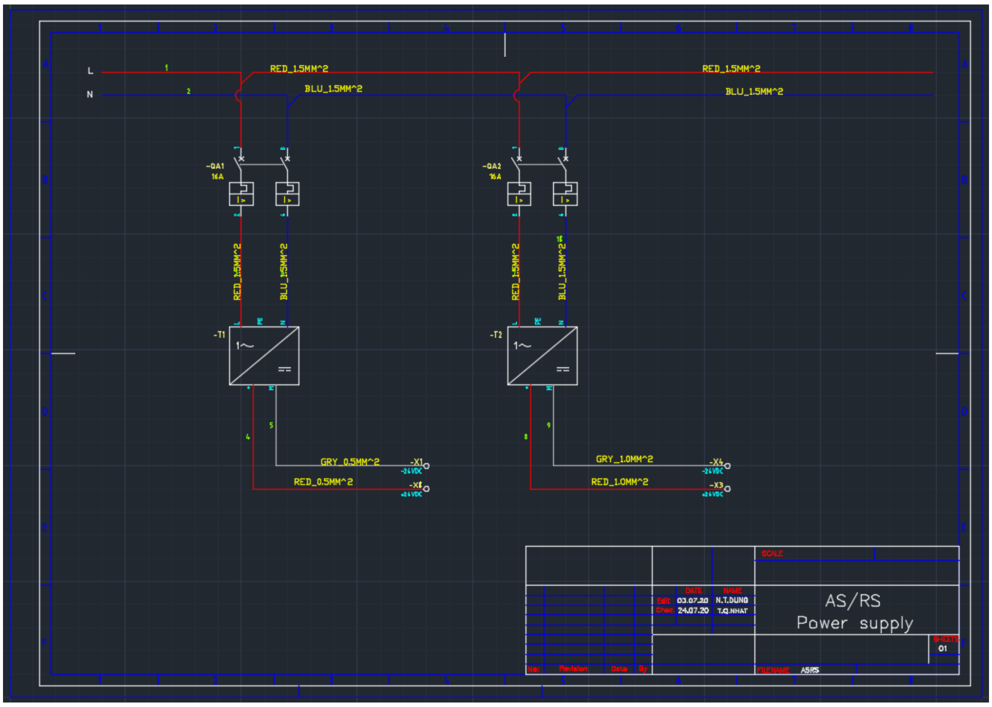


Figure 66. Power supply wiring diagram of the AS/RS

4.7.2 Input wiring diagram of PLC

In PLC Siemens S7 1214 dc/dc/dc, inputs can be either Sourcing or Sinking type. Hence, sourcing wiring connection was conducted for the PLC's input due to its popularity in industrial applications and wide availability of NPN sensors (shown in Figure 67).

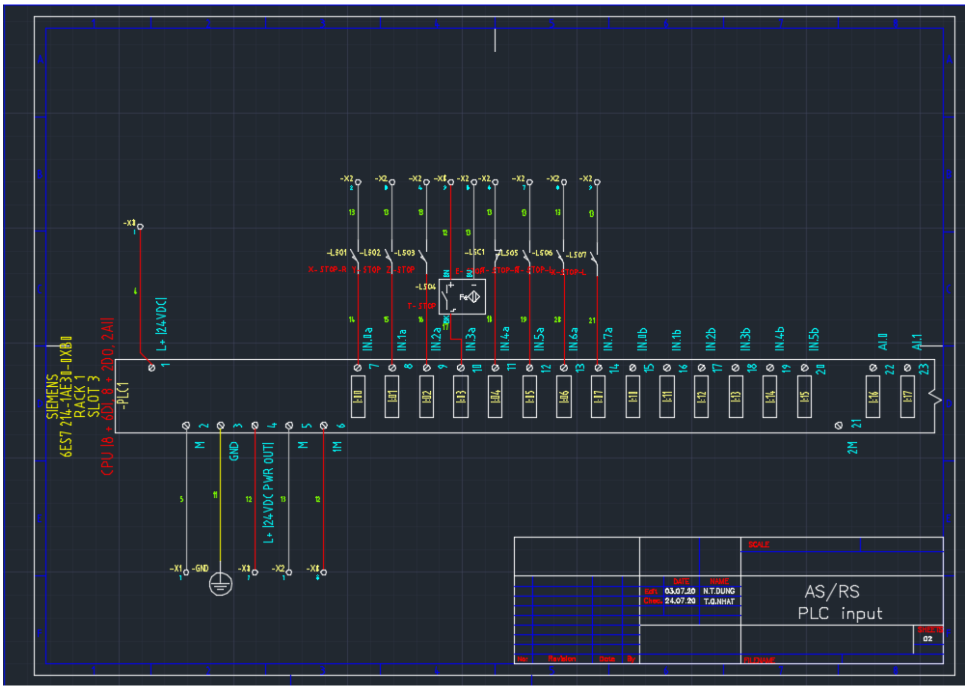


Figure 67. PLC's Input wiring diagram of the AS/RS

4.7.3 Output wiring diagram of PLC

During implementation, several malfunctions were spotted in the PLC module. The output signals from the PLC's pins Q0.2 and Q0.4 were repeatedly unstable. For this reason, the drivers did not receive enough continuous highspeed-pulse from the PLC to drive the motors. To overcome this situation, pulse signals from output Q0.0 were continuously provided in parallel to all four stepper motor drivers. However, because the nominal voltage supply of the driver was only +5VDC, a number of current limiting resistors must be added to ensure the driver's safety. According to the manufacturer's manual (DFRobot, n.d.), an advisable 8-15 mA current should be allowed for a proper operation of the internal chip (illustrated in Figure 68).

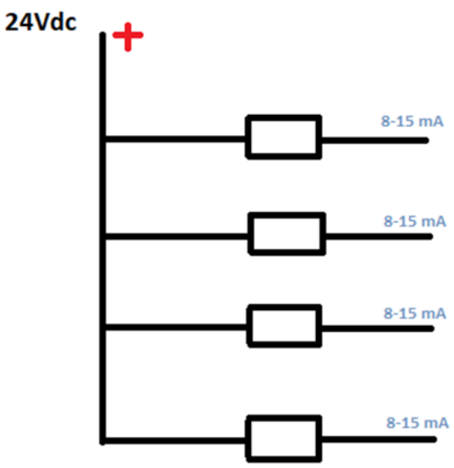


Figure 68. Parallel wiring connection with resistors

The persistence of voltage across each component in parallel circuit formed the equation:

$$R_{max} = \frac{U}{I} = \frac{24}{0.008} = 3000\ Ohm \quad (5)$$

$$R_{max} = \frac{U}{I} = \frac{24}{0.015} = 1600\ Ohm \quad (6)$$

$$\Longrightarrow 1600\ Ohm\ < R_{Recommended} < 3000\ Ohm \quad (7)$$

2200 Ohm resistor was suitable to limit the current to nearly 11 mA. Additionally, since the PLC's outputs were 24 Vdc:

$$P = \frac{U^2}{R} = \frac{24^2}{2200} \approx 0.262\ W \quad (8)$$

Accordingly, 2200 Ohm ½ W Resistors were selected to be added before the drivers' "Pulse +" pins.

Moreover, another set of transistors that acted as highspeed switches were added to the drivers' negative side to control the drivers' states. The maximum current rating of the transistor's base was 2A, plus, the current flew through each stepper driver was adjusted before coming to the "Pulse +" pin. Therefore, extra resistors were not necessary. However, to achieve another layer of protection, 2200 Ohm ½ W resistors were still added before the transistors (illustrated in Figure 69).

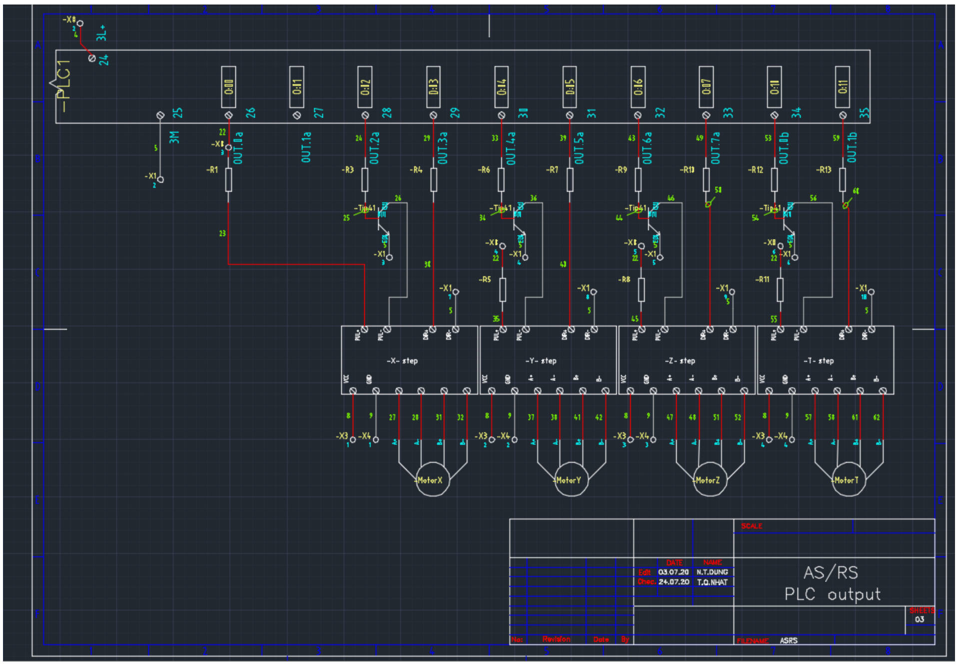


Figure 69. PLC's output wiring diagram of the AS/RS

4.7.4 Terminal blocks

Terminal blocks were mounted for several purposes. Since the PLC's terminal could only allow a limited number of incoming wires. It was advisable to use only one or two wires per terminal to avoid loose connection. Furthermore, terminal blocks provided a safe power distribution and connection, which reduced the risk of a short circuit.

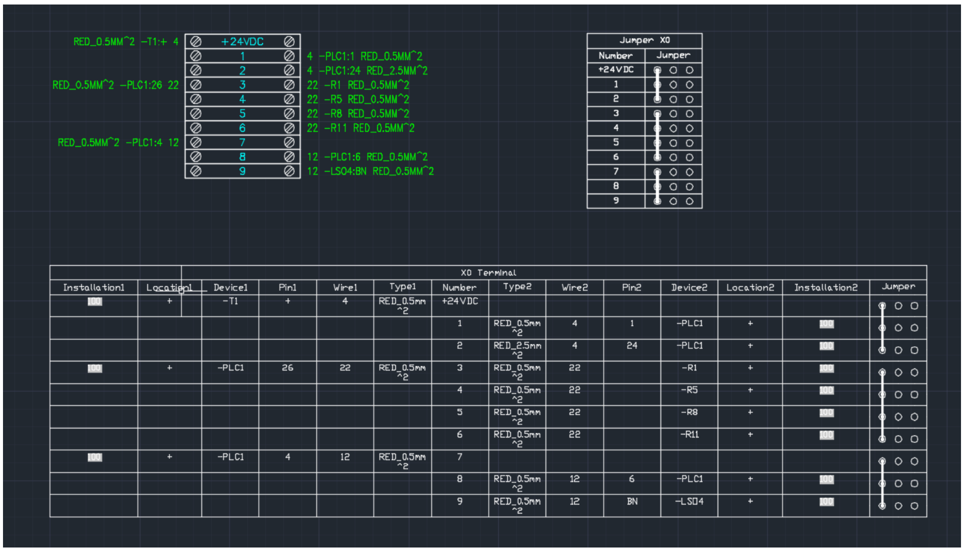


Figure 70. Terminal 0 connection

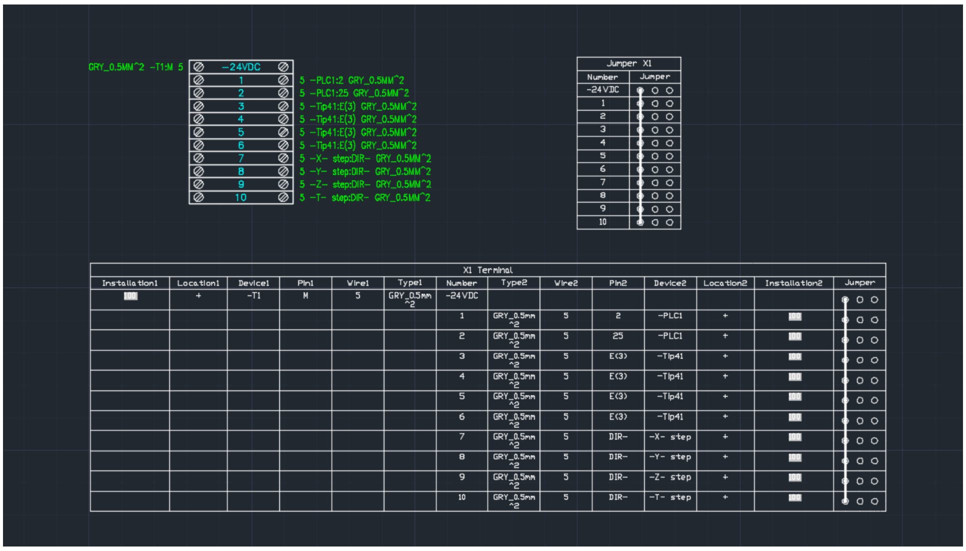


Figure 71. Terminal 1 connection

Figure 72. Terminal 2 connection

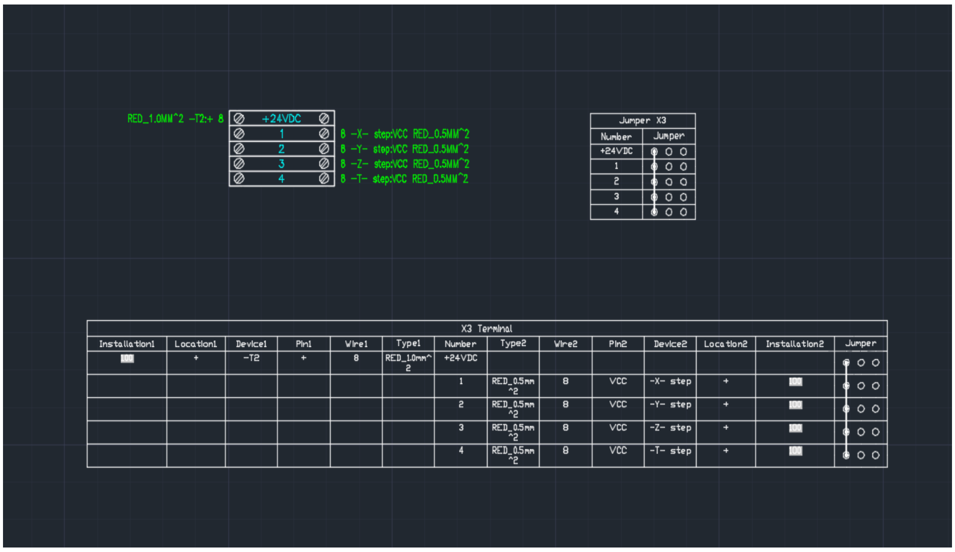


Figure 73. Terminal 3 connection

Figure 74. Terminal 4 connection

4.7.5 Control cabinet

A 500x400x210 mm control cabinet was selected which provided enough room for the set up of the components. Then, a set of 25x80 cable ducts was attached across the panel to organize cable routing before assembling other electrical parts.

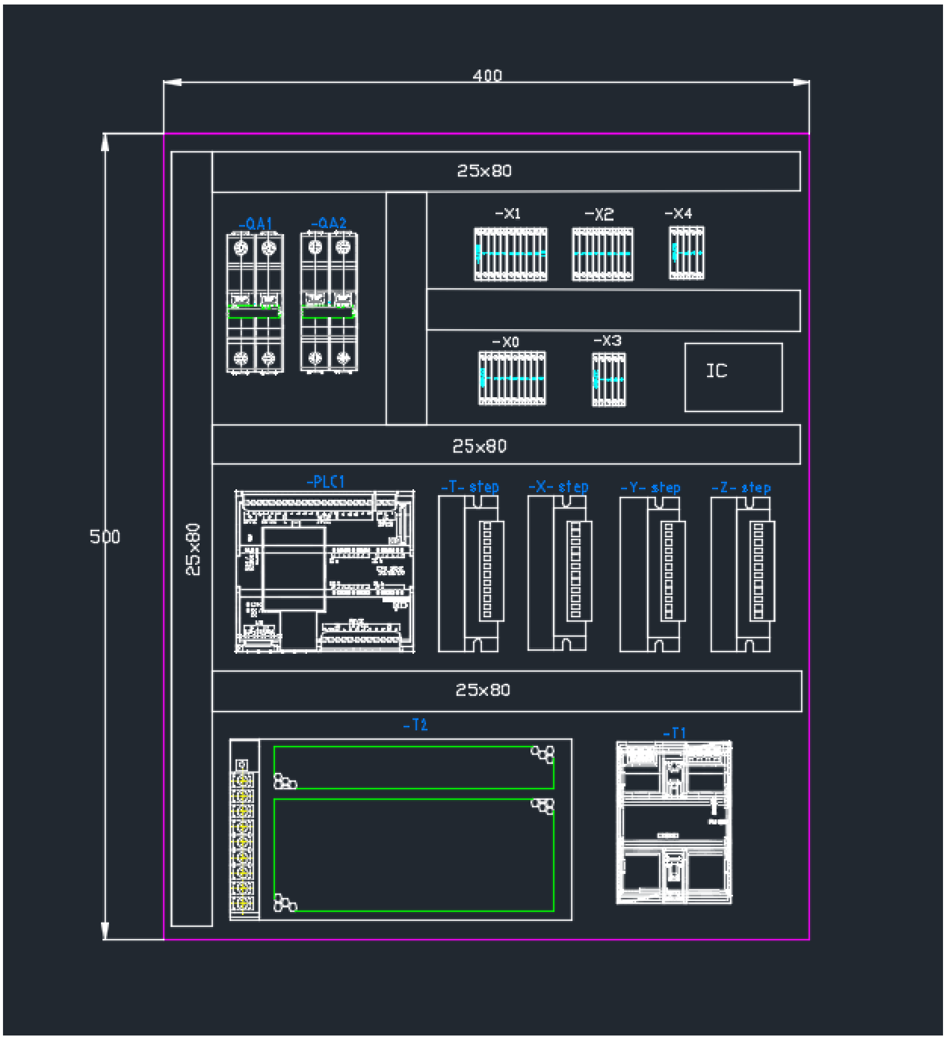


Figure 75. Cabinet layout

TAGS	QTY	SUB	CATALOG	MFG	DESCRIPTION
-QA1 -QA2	2		S 201-B 16 NA	ABB	S200 MINIATURE CIRCUIT BREAKER, PRO M COMPACT 1-POLE+N CIRCUIT BREAKER 16AMPS B-TRIP CHARACTERISTICS - CABLE PROTECTION 480Y/277VAC, INTERRUPTING CAPACITY: 6kA, DIN RAIL MOUNTING
-T- step -X- step -Y- step -Z- step	4		TB6600	DFRobot	9-24VDC, INPUT CURRENT 0-0.5A, OUTPUT CURRENT 0.5-4.0A, DC DRIVE STEPPER MOTOR DRIVE 160W
-LSO1 -LSO2 -LSO3 -LSO5 -LSO6 -LSO7	6		LXW5-11G2	RHENES	MICRO LIMIT SWITCH PARALLEL ROLLER PLUNGER SHORT HINGE ROLLER LEVER LINEAR 1NO 1NC
-MotorT -MotorZ	2		17PM-K342U	MINEBEA	STEPPING MOTOR, PRECISION HYBRID, 42x42x38, STEP ANGLE 1.8 , BALL BEARING DC STEPPER MOTOR 33.6W 24VDC UNI-POLAR, RATED CURRENT 1.4A, HOLDING TORQUE 250mNm, ROTOR INERTIA 75g.cm2
-MotorX -MotorY	2		17PM-K442U	MINEBEA	STEPPING MOTOR, PRECISION HYBRID, 42x42x48, STEP ANGLE 1.8 , BALL BEARING DC STEPPER MOTOR 33.6W 24VDC UNI-POLAR, RATED CURRENT 1.4A, HOLDING TORQUE 400mNm, ROTOR INERTIA 75g.cm2
-PLC1	1		6ES7 214-1AE30-0XB0	SIEMENS	SIMATIC S7-1200 - CPU1214C DC/DC/DC SIMATIC S7-1200 CPU 20.4-28.8VDC, DI: 24VDC/4mA, DO: 20.4-28.8VDC, AI: 0-10V ON-BOARD 14 DI / 10 DO + 2 AI
-T2	1		S8FS-C20024D	OMRON	OMRON SWITCH MODE POWER SUPPLY 24VDC/8.8A SINGLE-PHASE 24VDC, 200W, 100-120 VAC INPUT, 200-240 VAC INPUT POWER SUPPLY MODULE
-T1	1		6EP1332-1SH71	SIEMENS	SIMATIC S7-1200 POWER MODULE PM1207 STABILIZED POWER SUPPLY 24VDC/2.5A SINGLE-PHASE 24VDC, 60W, 120/230 VAC INPUT VOLTAGE POWER SUPPLY MODULE
-LSO4	1		LJ12A3-4-Z/BX	LEFIRCKO	PROXIMITY SENSOR, 3-WIRE DC, PLASTIC FACE PROXIMITY SENSOR - INDUCTIVE 6-36VDC BARREL DIAMETER: 12mm, NOMINAL SENSING DISTANCE: 4mm OUTPUT FUNCTION - N/O, NPN
-R1 -R10 -R11 -R12 -R13 -R3 -R4 -R5 -R6 -R7 -R8 -R9	12		CR-25	UNIOHM	CARBON FILM RESISTOR - 2200 ohm - 1/4W CARBON FILM 0.25W
-Tip41	4		TIP41C	ON SEMICONDUCTOR	MAX RATING Vcbo=100V,Vceo=100V,Vebo=5V,Ic=6A,Icp=10A,Ib=2A NPN EXPITAXIAL SILICON TRANSISTOR Pd=65W

Figure 76. Bill of material

5 PLC PROGRAMMING

Chapter 5 emphasizes the reason for using PLC Siemens S7-1200 and the sequence of steps for the configuration and structure of the program used in this thesis.

5.1 Overview of PLC (Programmable Logic Controller)

The controller chosen for this project is PLC Siemens SIMATICS S7-1200, which is commonly used in many industrials in practice. As an alternative replacement for S7-200, S7-1200 has predominant features. S7-1200 controllers are one of the product lines of programmable logic controllers (PLCs) for automation applications. Compact design, low cost, and powerful integrated function are what S7-1200 is designed for. PROFINET are predominant features of S7-1200 over S7-200 and other previous versions in terms of high-speed counter and pulse-train output (PTO).

S7-1200 PLC CPU consists of a microprocessor, a power supply, digital inputs/outputs, analog inputs, built-in PROFINET. All CPUs provide password protection to help prevent CPU and control programs from unauthorized access; the feature 'know-how protection' protects the code within a specific block.

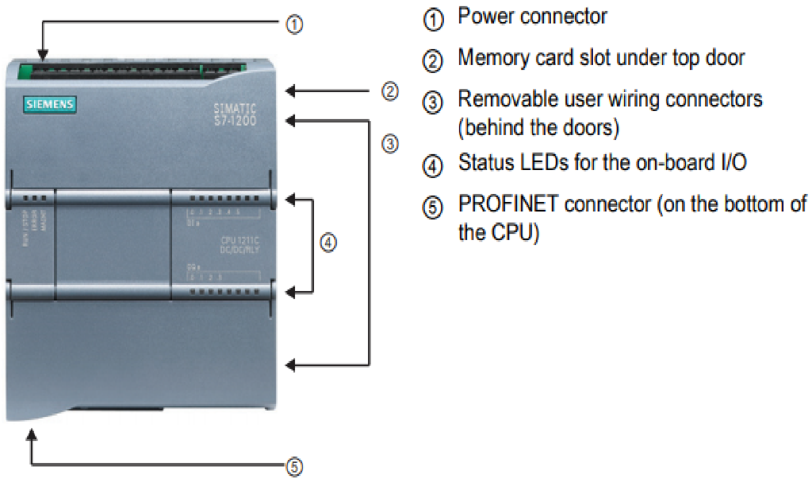


Figure 77. PLC Siemens S7-1200 (Siemens, 2015, p. 19)

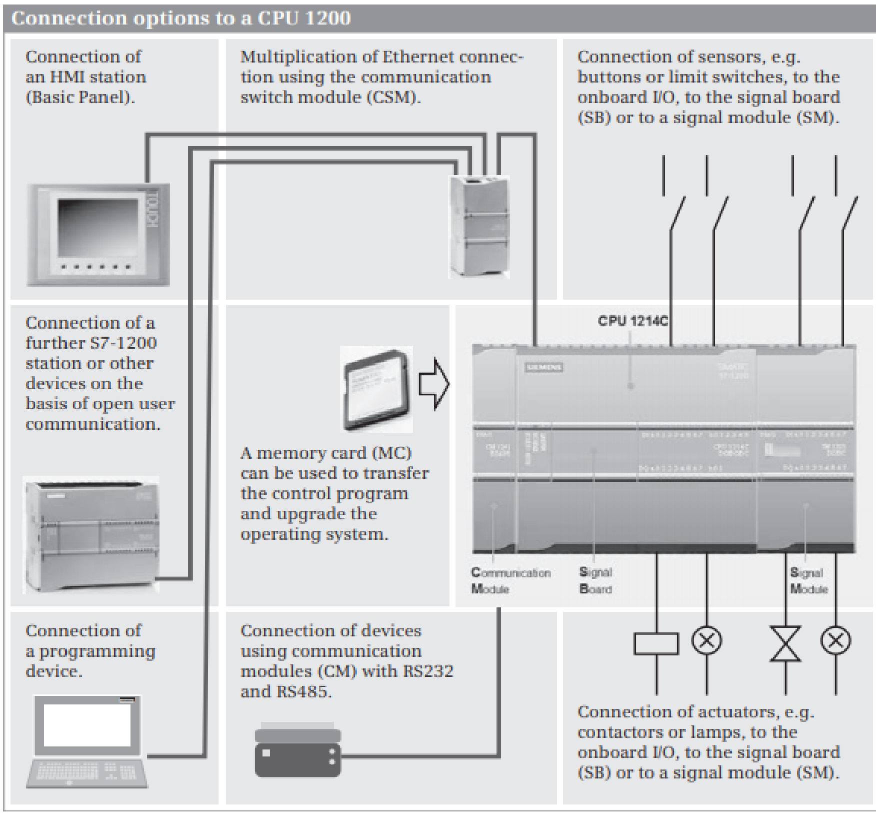


Figure 78. Some connection features of PLC Siemens S7-1200 (Siemens, 2015)

The software for programming S7-1200 supports three programming languages**:** Ladder Logic (LAD), Function Block Diagrams (FBD), Structured Control Language (SCL). The software has significant flexibility as it is integrated into Siemens TIA Portal version 15, which includes programming environment WinCC, Step 7 and HMI console in a single platform. In other words, working with S7-1200 in terms of programming software requires only TIA Portal.

SIMATICS S7-1200 has four distinct CPU models: 1211C, 1212C, 1214C and 1215C. Each has a different order number. All of the highlighted features of S7-1200 needed for this design are shown in Table 9. In this thesis, the model is SIMATICS S7-1200 CPU 1214C DC/DC/DC 6ES7 214-1AG31-0XB0 and the program is written by Ladder Logic (LAD) in TIA Portal V15.

Table 9. Features of Siemens related to this thesis (Siemens, 2020)

Feature	**S7-1200 CPU 1214C**	
Article number	6ES7 214-1AG31-0XB0	
Physical size (mm)	110 x 100 x 75	
Bit memory	8192 bytes	
Work memory	75 KB	
Signal module expansion	8	
Communication module (CM)	3	
Memory card	SIMATIC Memory card (optional)	
PROFINET Ethernet port	1	
Digital inputs	Quantity	14 6 High-Speed Counter
	Source/sink input	Yes
	Input voltage	Rated value: 24 V Signal 0: 5V DC at 1 mA Signal 1: 15 V DC at 2.5 mA
	Input current	1 mA
Digital outputs	Quantity	10 4 Pulse Train Output at 100 kHz
	Short-circuit protection	No
	Output voltage	Signal 0: 0.1 V Signal 1: 20 V
	Output current	Signal 0: 0.1 mA Signal 1: 0.5 A
Analog inputs	Quantity	2
Blocks	Type	OB, FB, FC, DB
	Size	100 Kbytes
Timers	Type	IEC
	Size	16 bytes per timer

5.2 Device configuration

Select the PLC CPU 1214C DC/DC/DC with article number 6ES7 214-1AG31-0XB0

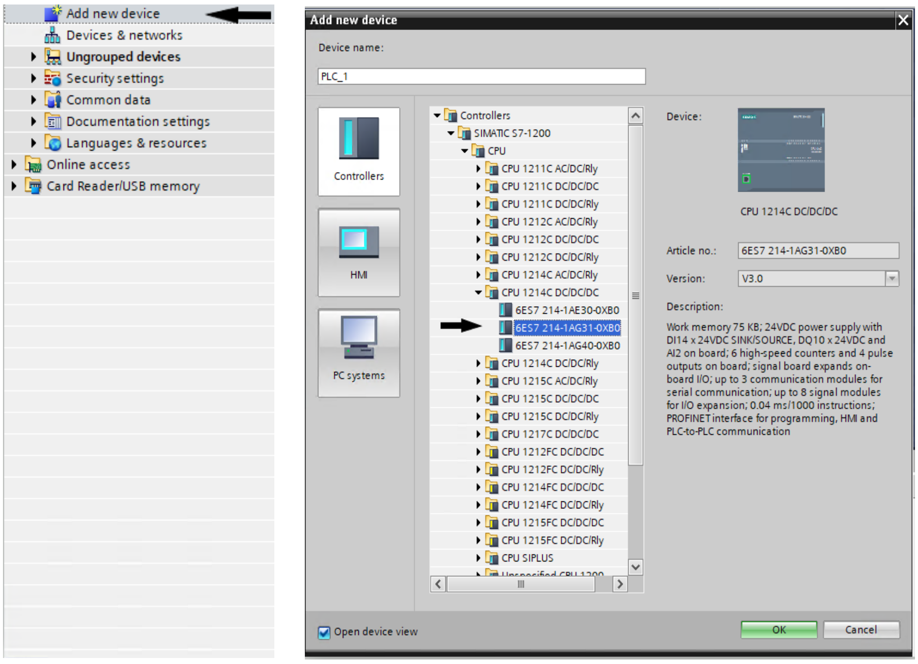


Figure 79. PLC configuration

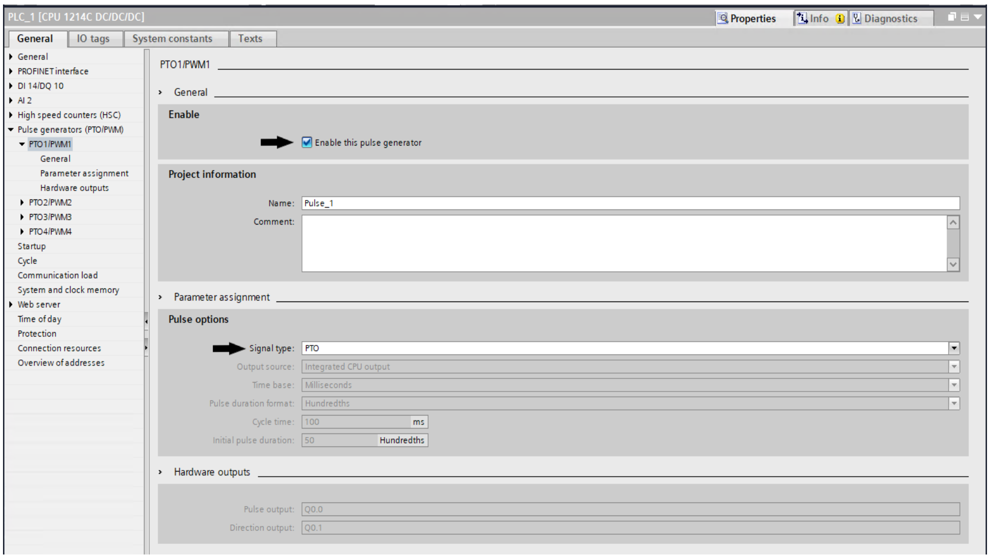


Figure 80. Pulse Train Output configuration

PLC S7-1200 has four pulse generators including two types of PTO (Pulse Train Output) and PWM (Pulse Width Modulation). However, only one PTO signal type was enabled, which is named "Pulse_1" (shown in Figure 80**)**. "Pulse_1" has two distinctly fixed outputs: a pulse output that is used to monitor the movement and pulse triggering of the motor (address Q0.0);

a direction out that controls the movement direction of the motor, which are both assigned automatically. The direction output (Q0.1) was not used in this project. However, because the output is automatically defined by TIA Portal, it is necessary to configure the output to avoid incoming errors. Specifically, this PTO "Pulse_1" was used to control the pulse of all four axes represented four stepper motors. (displayed in the next chapter 5.3)

5.3 Configuration of motion and technology objects

"Pulse_1" was previously created in the pulse interface while configuring the PLC S7-1200 device. As the pulse generator and direction of the stepper motor has been configured, the next step is to connect a technology object (also known as an "Axis" – shown in Figure 81) to "Pulse_1". This "Axis" connects the interface between the stepper motor and the user program.

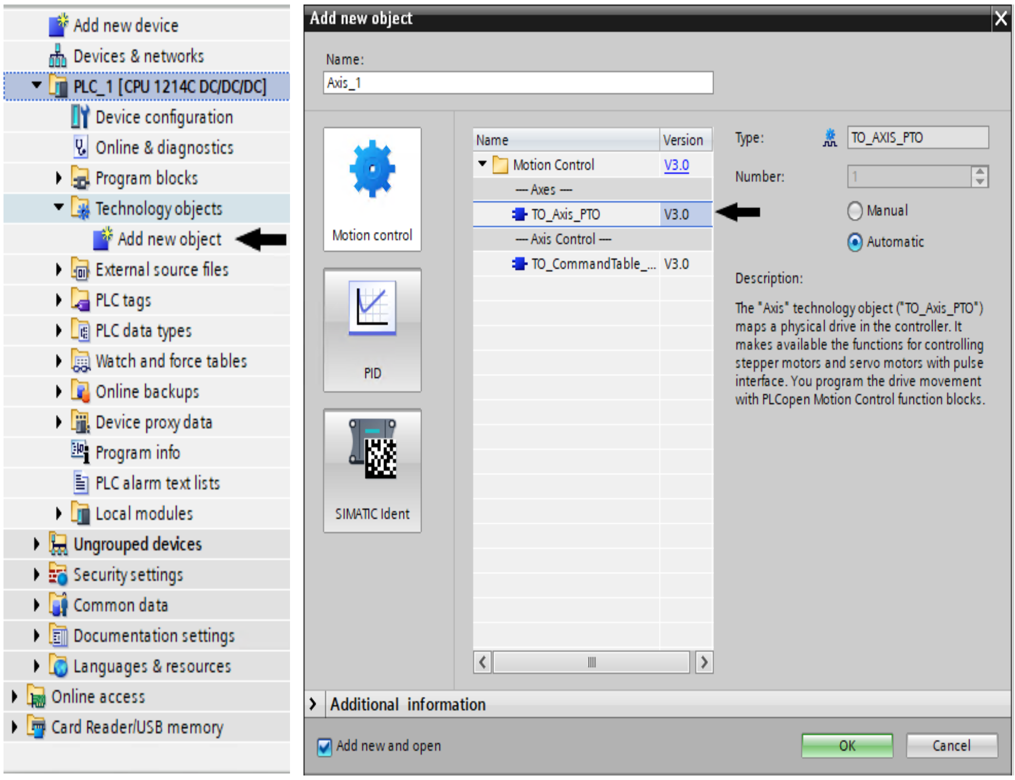


Figure 81. Create motion control axis for the stepper motor

The basic parameters of the technological object - "Axis_main" (shown in Figure 82) must be defined to completely configure the stepper motors while defining the extended parameters is optional. Assigning the "Axis_main" to the pulse generator "Pulse_1" will automatically generate the pulse output and the direction output, which have already been defined when configuring the device. The green tick (shown in Fig below) states that the stepper motors and the technological objects have been successfully configured, in other words, the stepper motor has been connected to the user program.

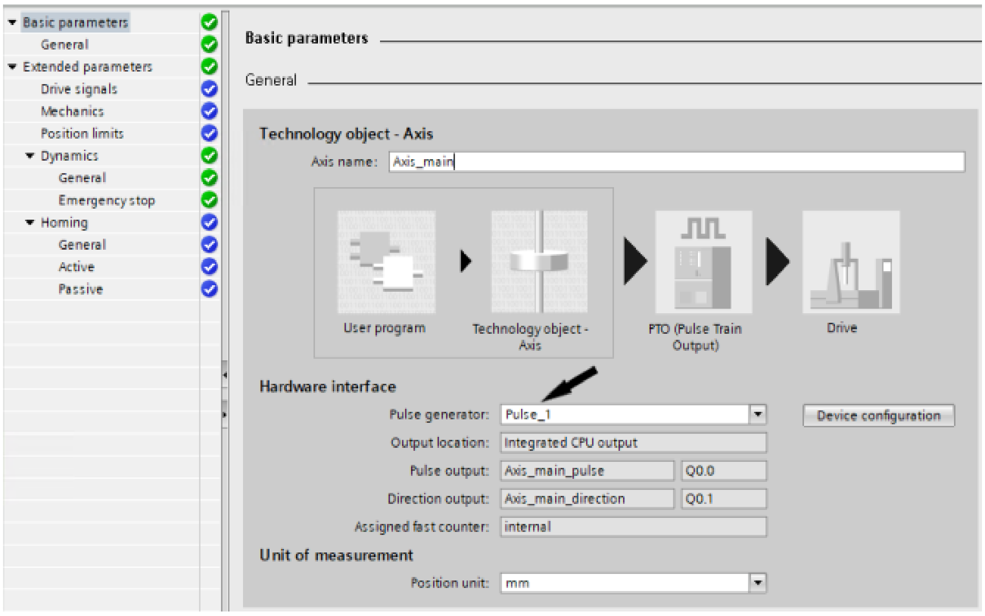


Figure 82. Technology objects configuration

The program can now control the pulse generator “Pulse_1”. The “MC_Power” function (Motion Control Power) displayed in Figure 83 is used to monitor the pulse generated from four stepper motors, based on the parameter “Enable”. The status of the variable “pulse_enable” ensures whether the program allows to enable or disable the pulse of the motors.

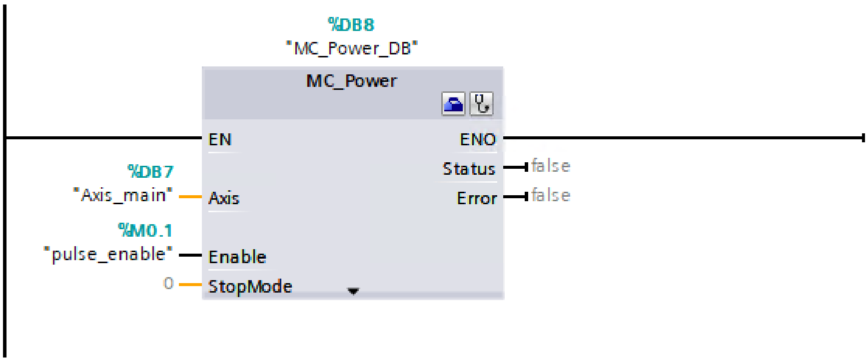


Figure 83. Create Motion Control Function for stepper motor

5.4 Variable structure

The design consists of two shelves (described in chapter 5.3), each shelf accommodates six slots (cells). Each cell from left to right and from up to down is assigned to a number from “1” to “12” respectively (shown in Figure 84).

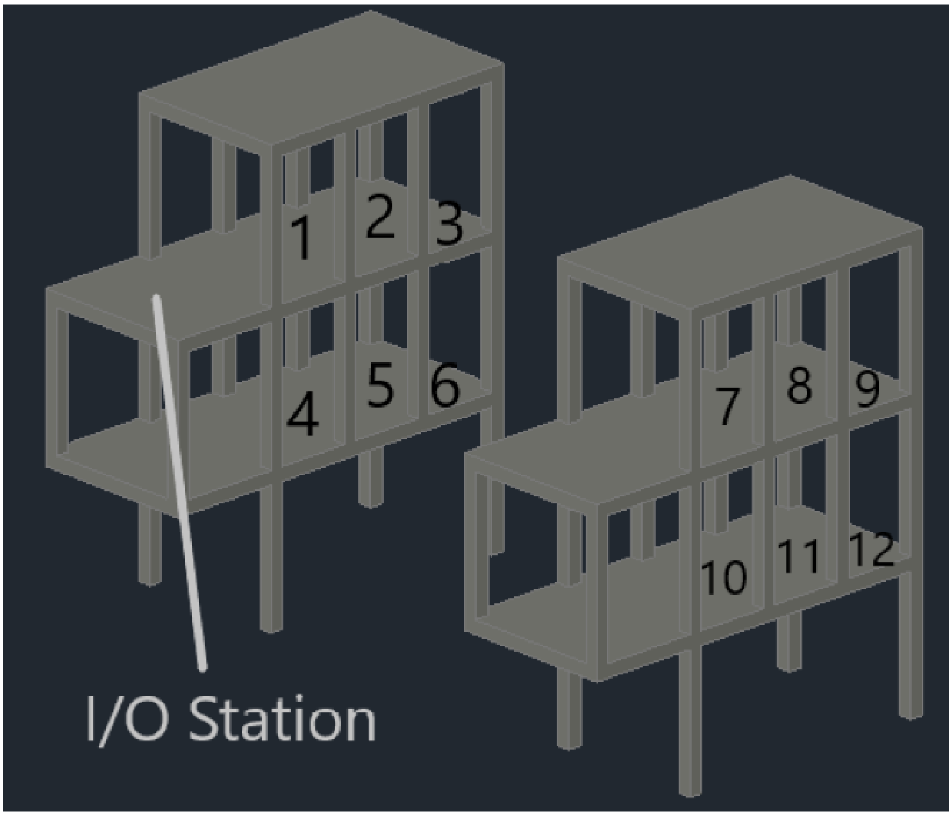


Figure 84. Cell position on both shelves

The HMI variables from “c1” to “c12” shown in Figure 85 displays the buttons where each button illustrates a cell assigned to the corresponding number (displayed in Figure 84). On the other hand, the variables from “lc1” to “lc12” are lights, which represent the status of that particular cell. In other words, light is ON if there is already an item at the cell and, on the contrary, light is OFF if that cell is vacant.

Figure 86 displayed all the inputs, outputs and memories used in the program. Seven of the inputs are limit switches, the corresponding stepper motor will stop when reaching the corresponding limit switch. The outputs “x_pusle”, “y_pulse”, “z_pulse” and “t_pulse” are used to enable or disable the pulse of the X-motor, Y-motor, Z-motor and T-motor, respectively. For instance, if “x_pulse” is 1, the motor runs; if “x_pulse” is 0, the motor stops. The direction of the motors was controlled by four outputs “x_dir”, “y_dir”, “z_dir” and “t_dir”. Each value of a direction output represents a unique direction of a specific motor, where each motor only has two directions. As a convention for easy understanding, the values of the direction outputs with respect to the movement direction were shown in Figure 85 and Figure 86.

hmi_data_block

	Name	Data type	Offset	Comment
1	▼ Static			
2	start	Bool	0.0	button: starts the program
3	stop	Bool	0.1	button: pause the program
4	home	Bool	0.2	button: set mode "home"
5	store	Bool	0.3	button: set mode "store"
6	retrieve	Bool	0.4	button: set mode "retrieve"
7	c1	Bool	0.5	button: cell 1
8	c2	Bool	0.6	button: cell 2
9	c3	Bool	0.7	button: cell 3
10	c4	Bool	1.0	button: cell 4
11	c5	Bool	1.1	button: cell 5
12	c6	Bool	1.2	button: cell 6
13	c7	Bool	1.3	button: cell 7
14	c8	Bool	1.4	button: cell 8
15	c9	Bool	1.5	button: cell 9
16	c10	Bool	1.6	button: cell 10
17	c11	Bool	1.7	button: cell 11
18	c12	Bool	2.0	button: cell 12
19	lc1	Bool	2.1	light: cell 1
20	lc2	Bool	2.2	light: cell 2
21	lc3	Bool	2.3	light: cell 3
22	lc4	Bool	2.4	light: cell 4
23	lc5	Bool	2.5	light: cell 5
24	lc6	Bool	2.6	light: cell 6
25	lc7	Bool	2.7	light: cell 7
26	lc8	Bool	3.0	light: cell 8
27	lc9	Bool	3.1	light: cell 9
28	lc10	Bool	3.2	light: cell 10
29	lc11	Bool	3.3	light: cell 11
30	lc12	Bool	3.4	light: cell 12

Figure 85. HMI variables

PLC tags

	Name	Tag table	Data type	Addr...	Retain	Acces...	Writa...	...	Comment
1	x_stop_right	Default tag table	Bool	%I0.0	☐	☑	☑	☑	limit switch on right side of X-axis
2	y_stop_down	Default tag table	Bool	%I0.1	☐	☑	☑	☑	limit switch at home of Y-axis
3	z_stop_up	Default tag table	Bool	%I0.2	☐	☑	☑	☑	limit switch above Z-axis
4	t_stop_mid	Default tag table	Bool	%I0.3	☐	☑	☑	☑	limit switch at the middle of T-axis
5	e_stop	Default tag table	Bool	%I0.4	☐	☑	☑	☑	emergency stop
6	t_stop_right	Default tag table	Bool	%I0.5	☐	☑	☑	☑	limit switch on right side of T-axis
7	t_stop_left	Default tag table	Bool	%I0.6	☐	☑	☑	☑	limit switch on left side of T-axis
8	x_stop_left	Default tag table	Bool	%I0.7	☐	☑	☑	☑	limit switch on left side of X-axis
9	Axis_main_pulse	Default tag table	Bool	%Q0.0	☐	☑	☑	☑	PTO output to generate the pulse for all axes
10	Axis_main_direction	Default tag table	Bool	%Q0.1	☐	☑	☑	☑	not in used (avoid errors)
11	x_pulse	Default tag table	Bool	%Q0.2	☐	☑	☑	☑	enable/disable the pulse of the X-motor
12	x_dir	Default tag table	Bool	%Q0.3	☐	☑	☑	☑	control direction (left/right) of the X-motor
13	y_pulse	Default tag table	Bool	%Q0.4	☐	☑	☑	☑	enable/disable the pulse of the Y-motor
14	y_dir	Default tag table	Bool	%Q0.5	☐	☑	☑	☑	control direction (forward/downward) of the Y-motor
15	z_pulse	Default tag table	Bool	%Q0.6	☐	☑	☑	☑	enable/disable the pulse of the Z-motor
16	z_dir	Default tag table	Bool	%Q0.7	☐	☑	☑	☑	control direction (up/down) of the Z-motor
17	t_pulse	Default tag table	Bool	%Q1.0	☐	☑	☑	☑	enable/disable the pulse of the T-motor
18	t_dir	Default tag table	Bool	%Q1.1	☐	☑	☑	☑	control direction (clockwise/counter-clockwise) of the T-motor
19	p_run	Default tag table	Bool	%M0.0	☐	☑	☑	☑	run the program
20	pulse_enable	Default tag table	Bool	%M0.1	☐	☑	☑	☑	enable pulse for the motion control axis
21	step_enable	Default tag table	Bool	%M0.2	☐	☑	☑	☑	check whether the system allows the step motor to run or not
22	p_busy	Default tag table	Bool	%M0.3	☐	☑	☑	☑	check when program is running or not
23	p_busy_retrieve_L	Default tag table	Bool	%M0.4	☐	☑	☑	☑	when program is running "retrieve left"
24	p_busy_retrieve_R	Default tag table	Bool	%M0.5	☐	☑	☑	☑	when program is running "retrieve right"
25	p_busy_store_L	Default tag table	Bool	%M0.6	☐	☑	☑	☑	when program is running "store left"
26	p_busy_store_R	Default tag table	Bool	%M0.7	☐	☑	☑	☑	when program is running "store right"
27	retrieve_L_finish	Default tag table	Bool	%M1.0	☐	☑	☑	☑	when "retrieve left" finishes
28	retrieve_R_finish	Default tag table	Bool	%M1.1	☐	☑	☑	☑	when "retrieve right" finishes
29	store_L_finish	Default tag table	Bool	%M1.2	☐	☑	☑	☑	when store left" finishes
30	store_R_finish	Default tag table	Bool	%M1.3	☐	☑	☑	☑	when "store right" finishes

Figure 86. Program variables

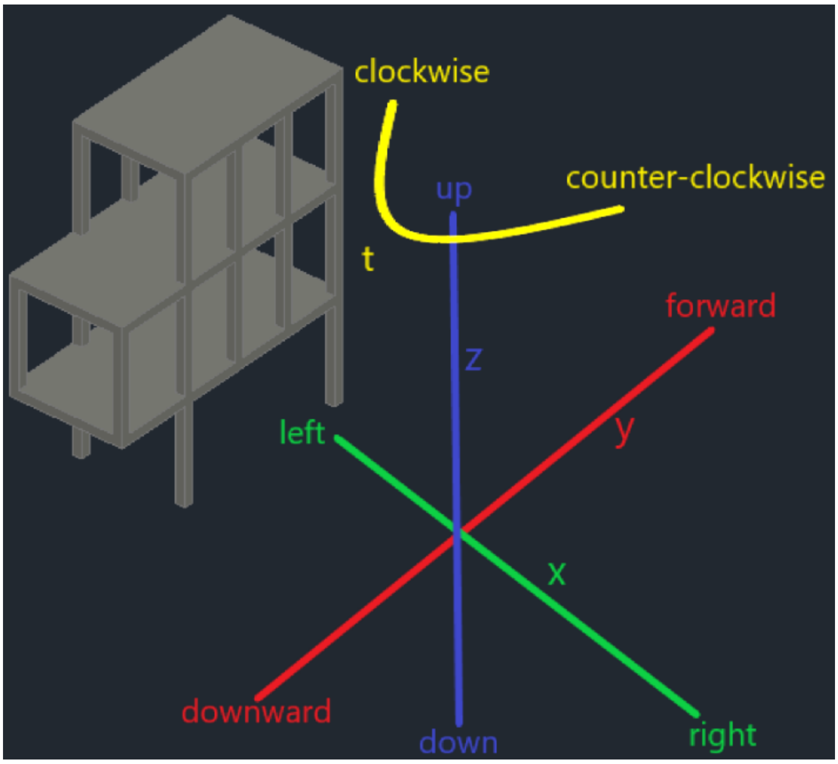


Figure 87. Movement directions of each axis

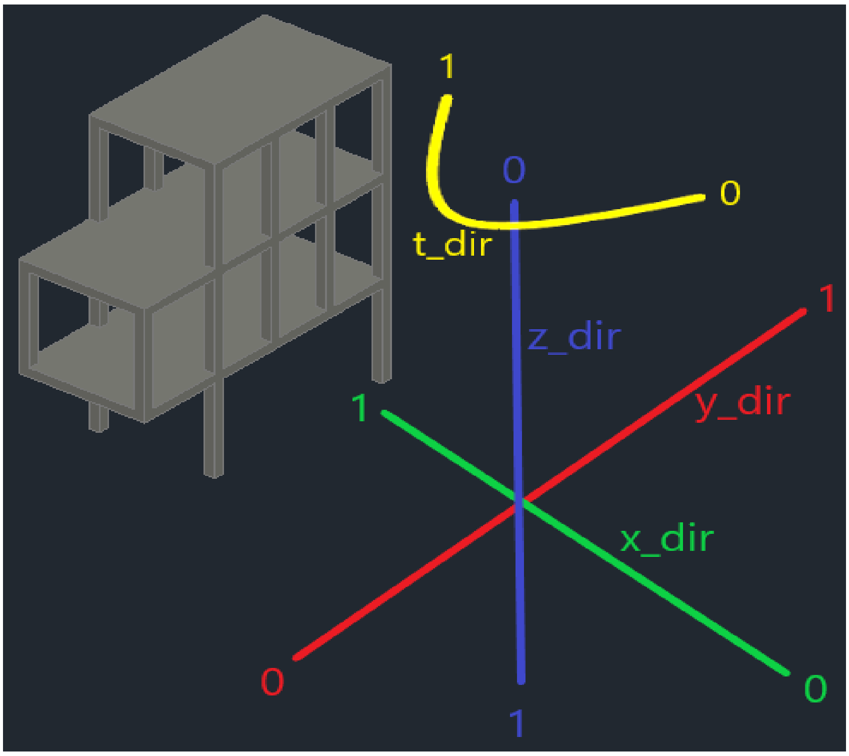


Figure 88. The value of the direction outputs (x_dir, y_dir, z_dir) when moving towards a particular direction

5.5 Program blocks

The programming structure was divided into two parts: main function blocks and subfunctions. The main function blocks contain five (Function Blocks) FBs represented five modes of the model.

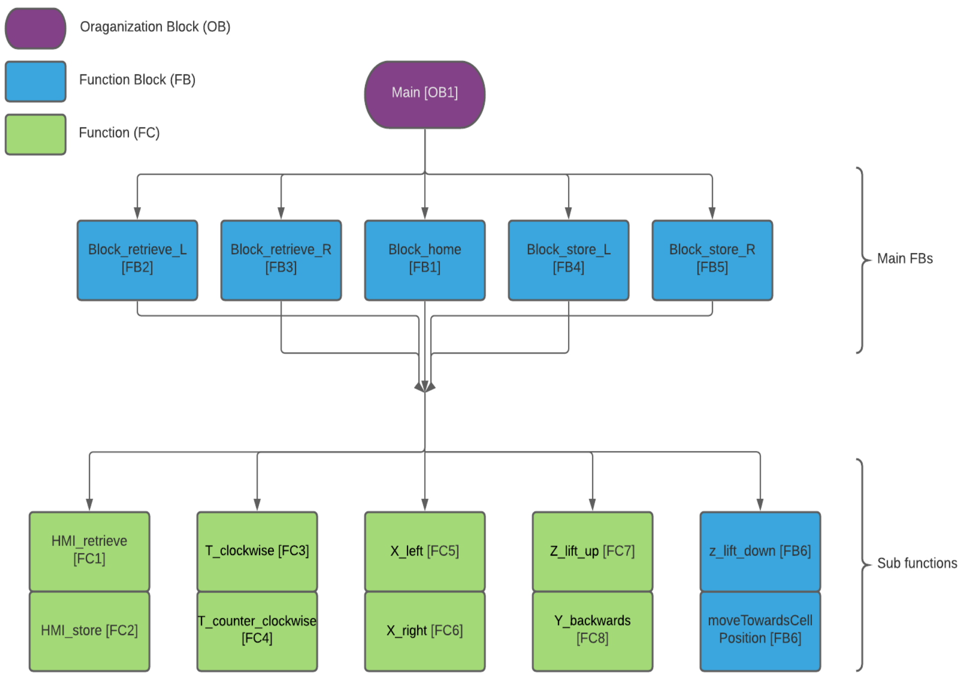


Figure 89. Hierarchy of program block calls

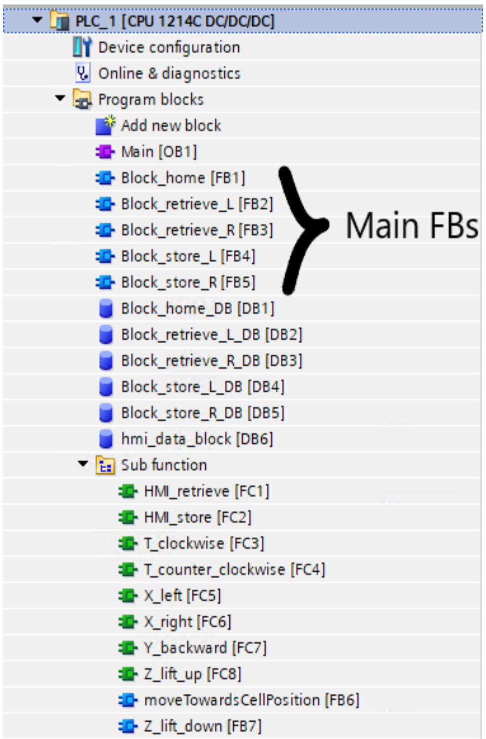


Figure 90. Structure program blocks

Table 10. Description the main FBs

FBs	Description
Block_ home [FB1]	Move towards home position (initial position of the S/R machine). The function is especially used in case of a blackout or a breakdown when the S/R machine is at a random position and the memories might be lost. The S/R machine will safely move towards the initial position
Block_ retrieve_L [FB2]	When there is an item on the chosen cell on the left shelf, the S/R machine travels to the cell position, carries the item and places it at the I/O station. If the chosen cell is empty, the function does not operate
Block_ retrieve_R [FB3]	When there is an item on the chosen cell on the right shelf, the S/R machine travels to the cell position, carries the item and places it at the I/O station. If the chosen cell is empty, the function does not operate
Block_ store_L [FB4]	When the chosen cell on the left shelf is empty, the S/R machine move towards the I/O station to pick up the items then travels to the cell position and places the item at that cell
Block_ store_R [FB5]	When the chosen cell on the right shelf is empty, the S/R machine move towards the I/O station to pick up the items travels to the cell position and places the item at that cell

The sub functions (inner functions) consist of different FCs and FBs.

Table 11. Description of all sub functions

Function	Description
HMI_retrieve	When the retrieving process at the selected cell finishes, the program turns off the lights of that cell on the HMI
HMI_store	When the storing process at the selected cell finishes, the program turns on the lights of that cell on the HMI
T_clockwise	Rotates the T-motor in a clockwise direction
T_counter_ clockwise	Rotates the T-motor in a counter-clockwise direction
X_left	Moves the X-motor to the left side
X_right	Moves the X-motor to the right side
Y_backward	Moves the Y-motor backwards
Z_lift_up	Moves the Z-motor upwards, specifically lifts the item up
Z_lift_down	Moves the Z-motor downwards, specifically places the item
moveTowards CellPosition	The function moves the Y-motor forwards to the chosen cell position. If the chosen cell is at the lower row, the function also moves the Z-motor downwards

5.6 Description of primary programming functions

The program starts to run when the “start” button on the HMI is pressed while the “stop” button and the emergency stop were not activated, then “p_run” is initiated, as shown in the LAD logic in Figure 91.

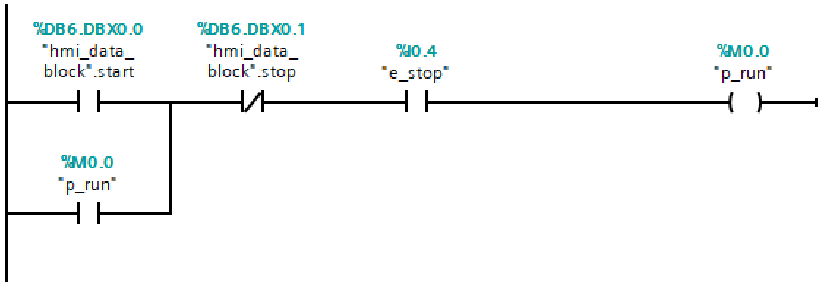


Figure 91. LAD logic for starting the program

The logic expression in Figure 92 illustrates that when the program stops running or finishes the process, all outputs are reset and all stepper motors are deactivated.

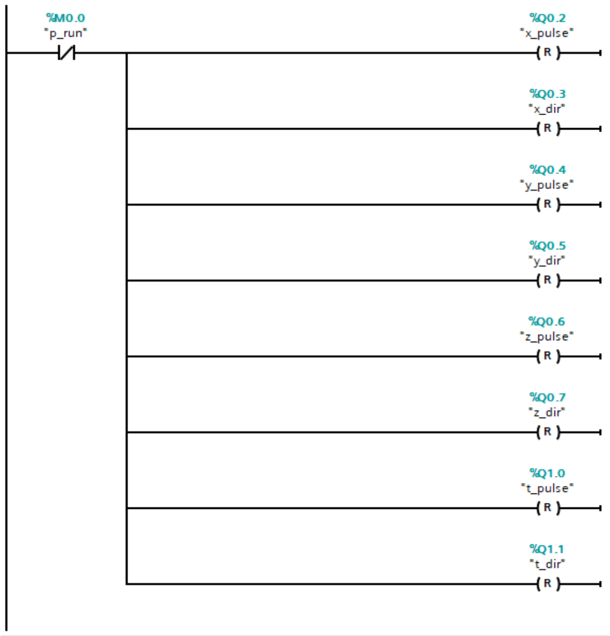


Figure 92. Reset all output when “p_run” is deactivated

The memory “pulse_enable” in Figure 93 triggers the pulse of the “Axis_main” (as described in Figure 82) to run the stepper motor. The variable “step_enable” decides whether to generate the pulse for the motor, “step_enable” is always set to “1” when the program is currently running. Due to possible hardware malfunctioning when the program is not running but the motor output is “1”, “step_enable” will disable the pulse generated for the motors.

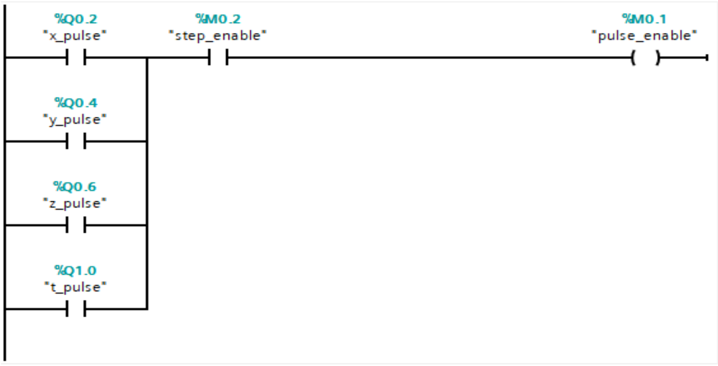


Figure 93. Enable the Pulse output to run the motor

Figure 94 and Figure 95 both illustrate the logic expression of the "store" mode**.** In order to activate the "store" mode, first "p_run" must be "1" (the program is running), the "Store" button and a button represented the chosen cell on the HMI, respectively, must be pressed one after another. However, the "Store" mode is not activated when the light of the chosen cell on the HMI is on ("lc" is "1"), which indicates that there is already an item on that cell. In other words, the "store" function is only called when there is no item on the chosen cell, as depicted in chapter 5.4

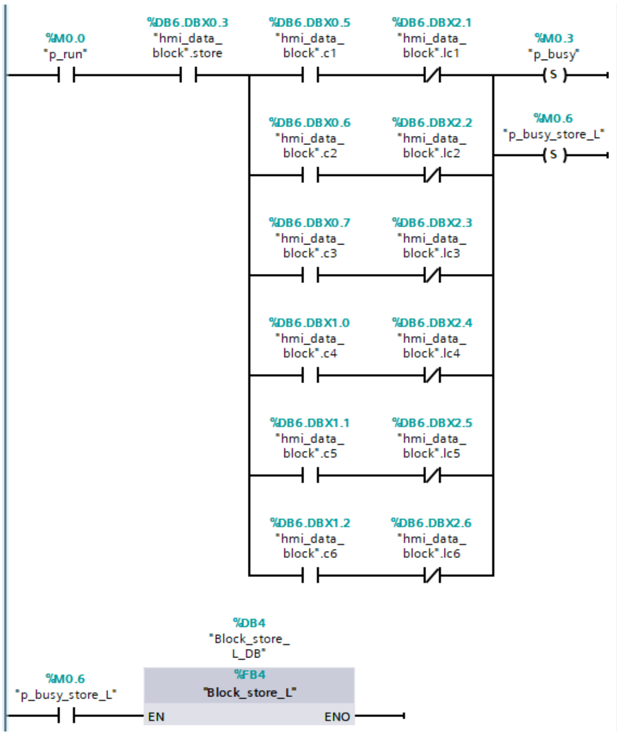


Figure 94. Run "Store" mode if the chosen cell is on the left shelf

Each cell is indexed to a number from 1 to 12, as shown in Figure 84**.** The cells numbered from 1 to 6 will call the "Block_store_L" Function Block (Figure 94) and the cells numbered from 7 to 12 will call the "Block_store_R" Function Block (Figure 95).

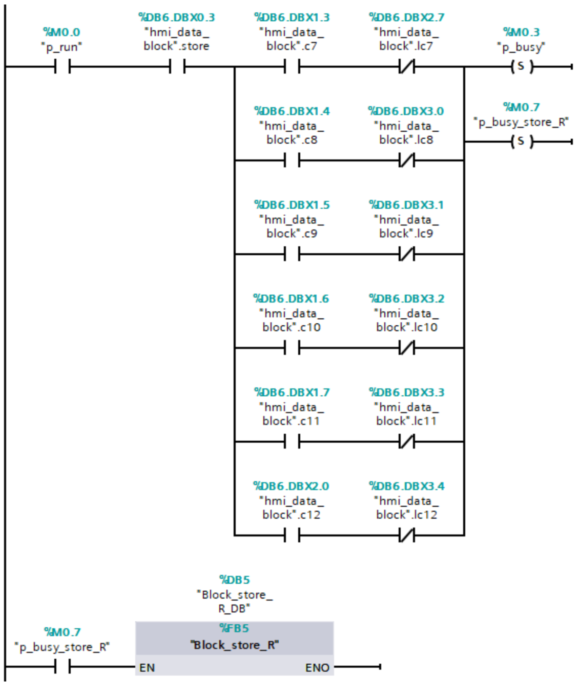


Figure 95. Run “Store” mode if the chosen cell is on the right shelf

The logic expressions of the “Retrieve” process displayed in Figure 96 and Figure 97 is relatively similar to the “Store” process. The sole difference is that the “Retrieve” mode only runs if there is an item at the chosen cell.

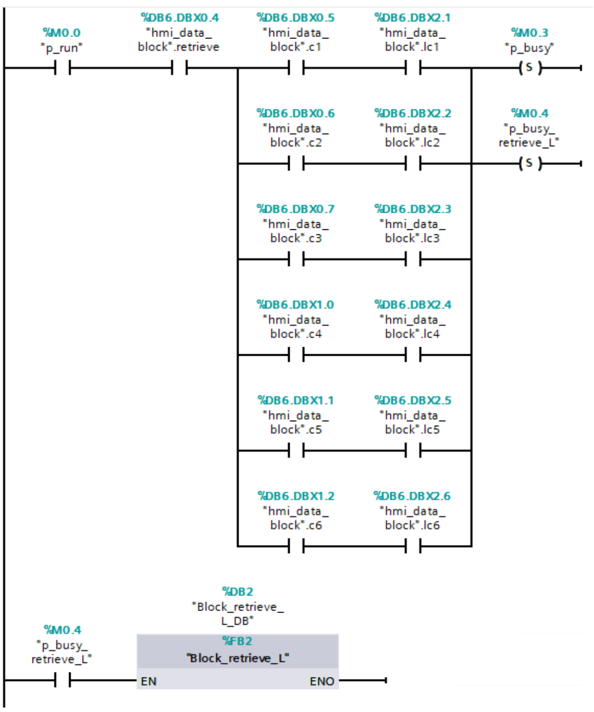


Figure 96. Run “Retrieve” mode if the chosen cell is on the left shelf

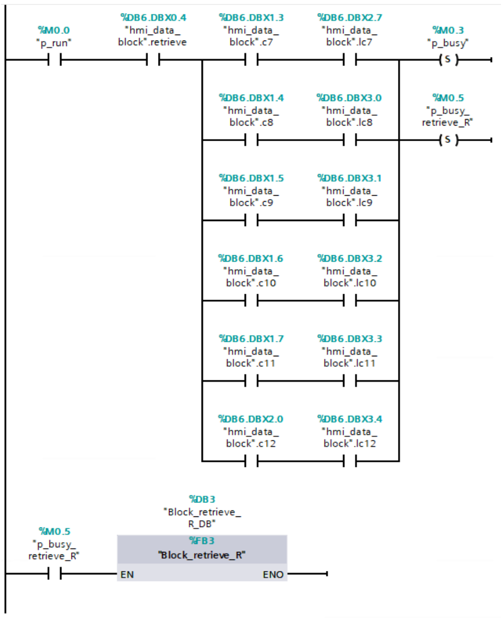


Figure 97. Run “Retrieve” mode if the chosen cell is on the right shelf

6 HMI DESIGN (HUMAN-MACHINE INTERFACE)

Weintek MT8071iP HMI as it was used for the user interface is widely compatible with a broad range of PLC brands, includes Siemens. The programming of HMI was done on Weintek Easybuilder pro. This HMI program offers high-quality graphics libraries, which makes editing becomes straightforward. Furthermore, Weintek HMI uses TCP/IP protocol, which enables the Ethernet connection.

Before connecting Siemens PLC to Weintek HMI, the data block for the HMI on TIA Portal was activated with offset addresses by unchecking the Optimized block access. Then to acquire data from PLC, linking devices was made in device settings of Easybuilder pro, S7-1200 device type was selected. Moreover, the Ip address must be checked carefully. To be able to obtain data from PLC, both PLC and the HMI settings need to be set at the same IP address, which shows in Figure 98.

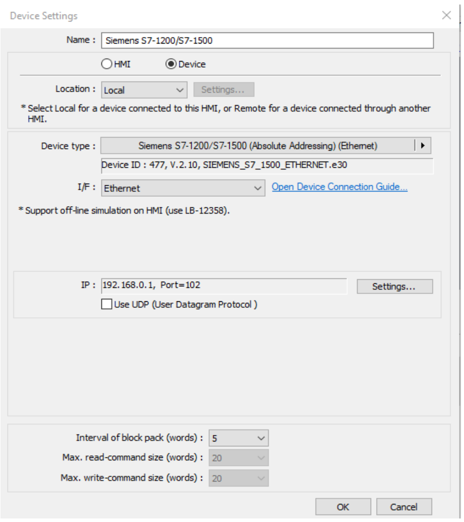


Figure 98. Device settings in Easybuilder pro

Importing tags was made after saving and closing the TIA portal project. Otherwise, it could not be done. All tags were imported at once on Easybuilder pro, which shortens the importing process.

The HMI mainly focuses on the simplicity in the design to effectively deliver enough information to the operators regardless of their familiarity with machines. The design was divided into two parts. The first part on the left side of the HMI was the arrangement of the shelves (displayed in Figure 84). It was equipped with selecting buttons and a number of lamps to illustrate the cell's state. The second part on the right side was the control area includes START, STOP, HOME, RETRIEVE, and STORE buttons (Figure 99).

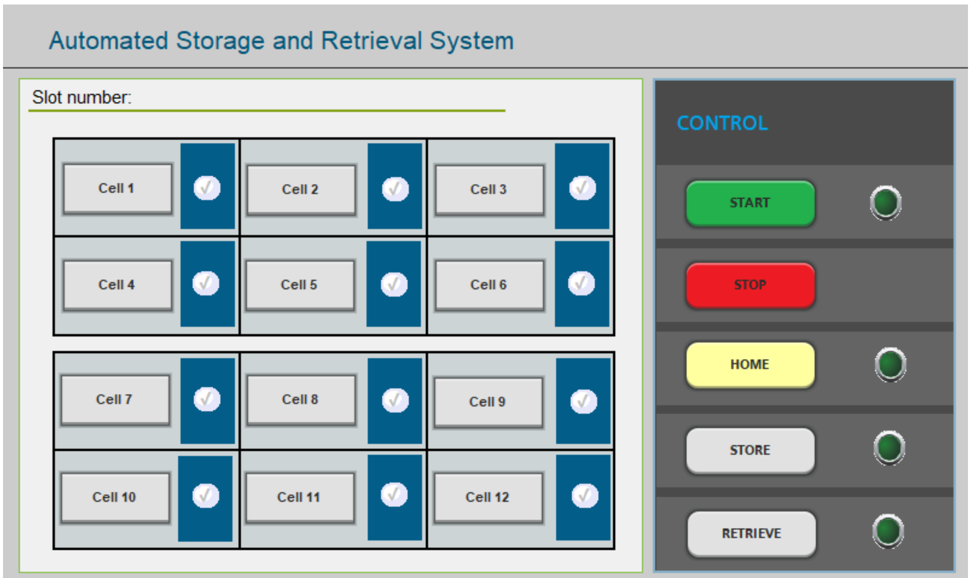


Figure 99. HMI interface of the AS/RS

7 FURTHER IMPROVEMENTS OF THE PROJECT

7.1 Experimental result

The planning process had an essential influence on the implementation of the project, which was defined and evaluated in terms of available components provided by the commissioning party. The final target of the project was achieved and the model was approved by the supervisors of the company. Figure 100 and Figure 101 show different views of the real model.

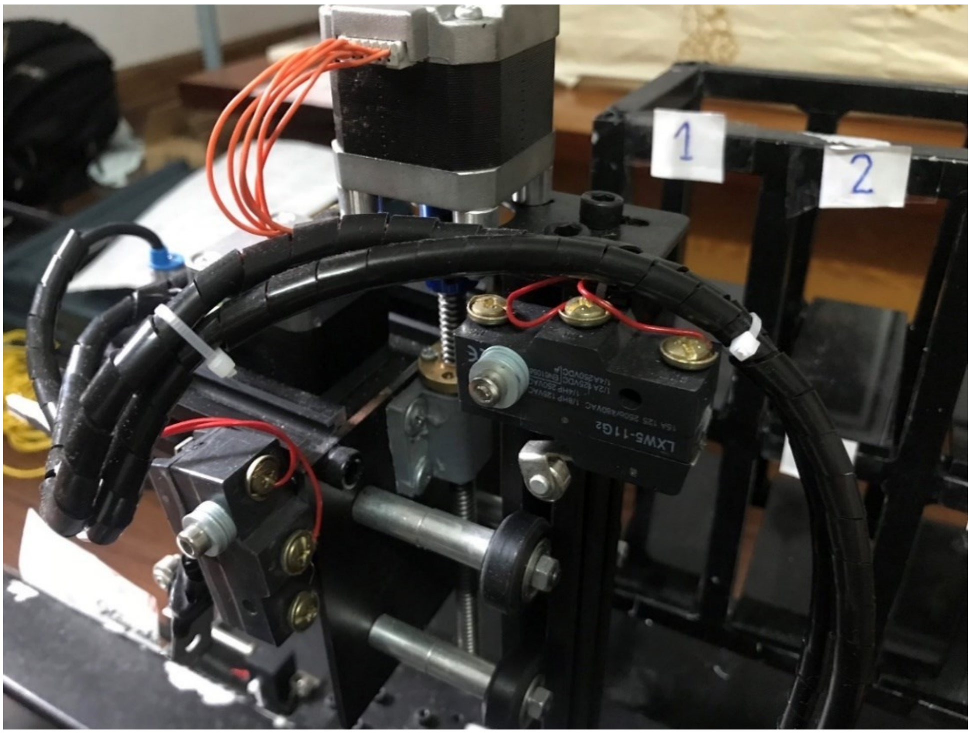


Figure 100. Back view of Z-axis

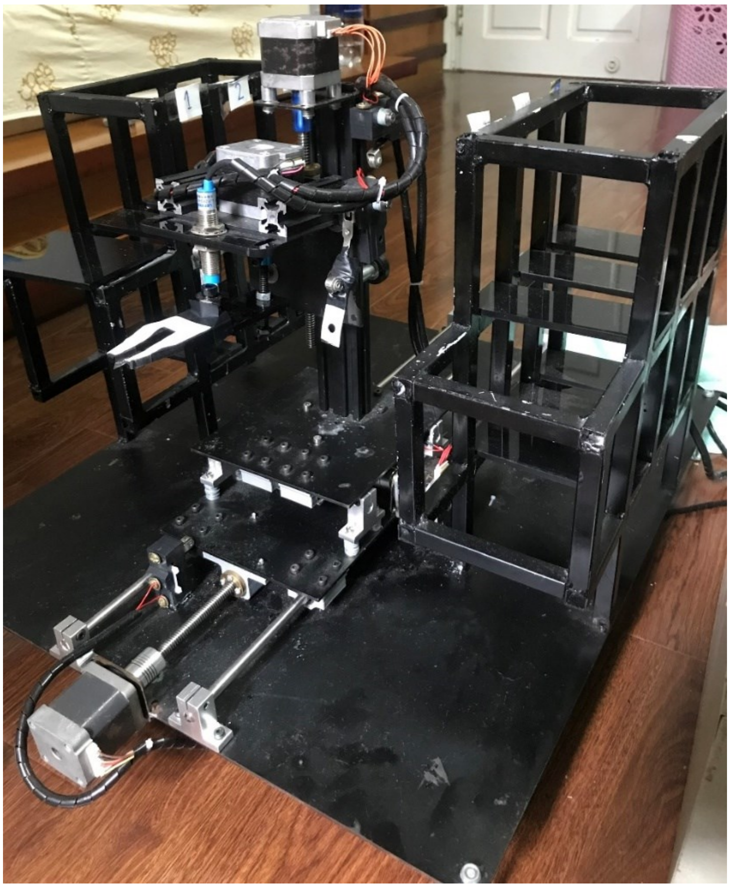


Figure 101. Overview of the AS/RS

7.2 Drawbacks in the project

During the procedure of the project, the main challenges when designing the layout were the lack of limit switches and some critical components provided by the commissioning party. The supervisor of the company stated that at the moment the project should be able to operate as soon as possible for visualization and training programs. Therefore, the system will be upgraded at the next stage of the project when the commissioning party decides to conduct more research and investments.

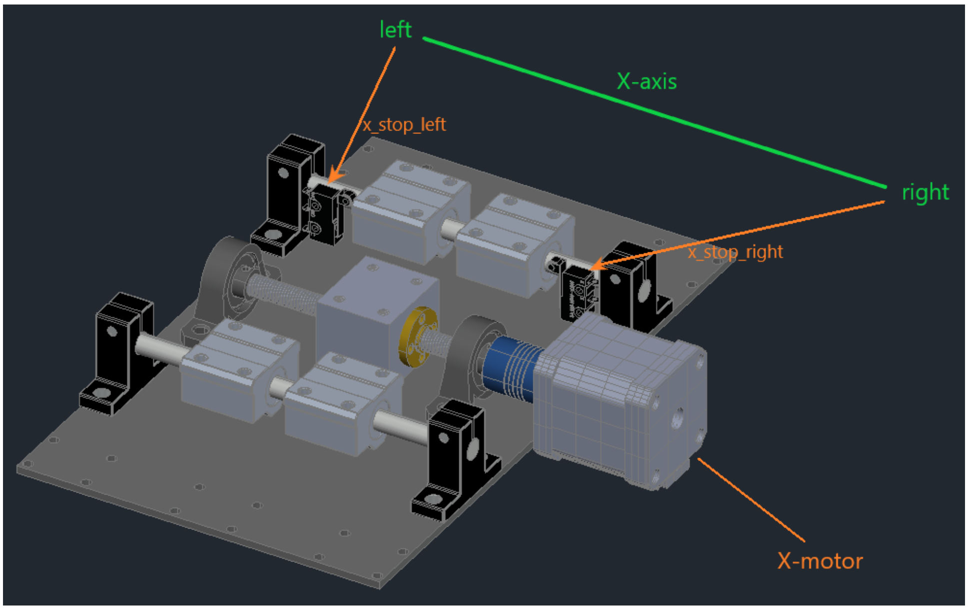


Figure 102. The X-axis of the current system

Figure 102 shows that the movement the X-motor along the X-axis is limited by two limit switches. Since there is no limit switch in the middle between the two shelves (in the middle of the X-axis), the origin of the Y-axis cannot be placed here. Instead, it was positioned closer to the right shelf. Therefore, when implementing the “store” or “retrieve” process, the system had to be shifted to the left along the X-axis in order to prevent the T-axis from being stuck into the right shelf (as depicted in Figure 103 and Figure 104).

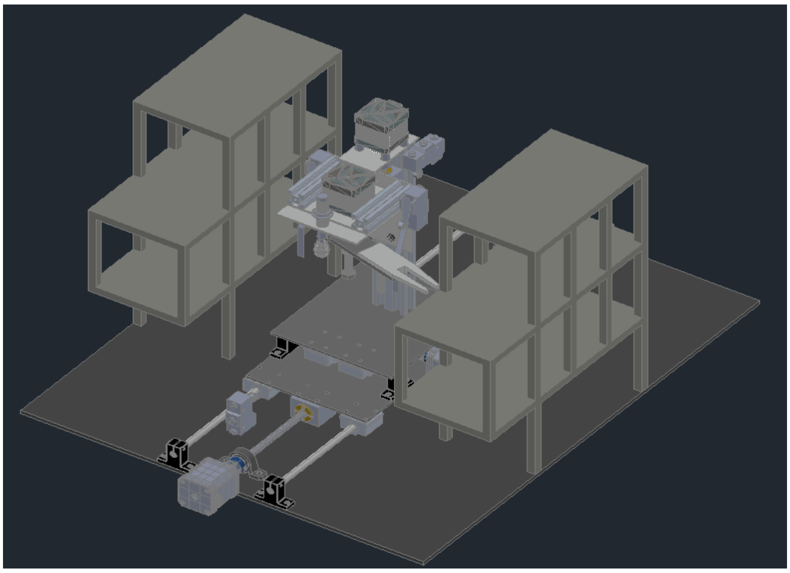


Figure 103. T-axis collides with the right hand shelf

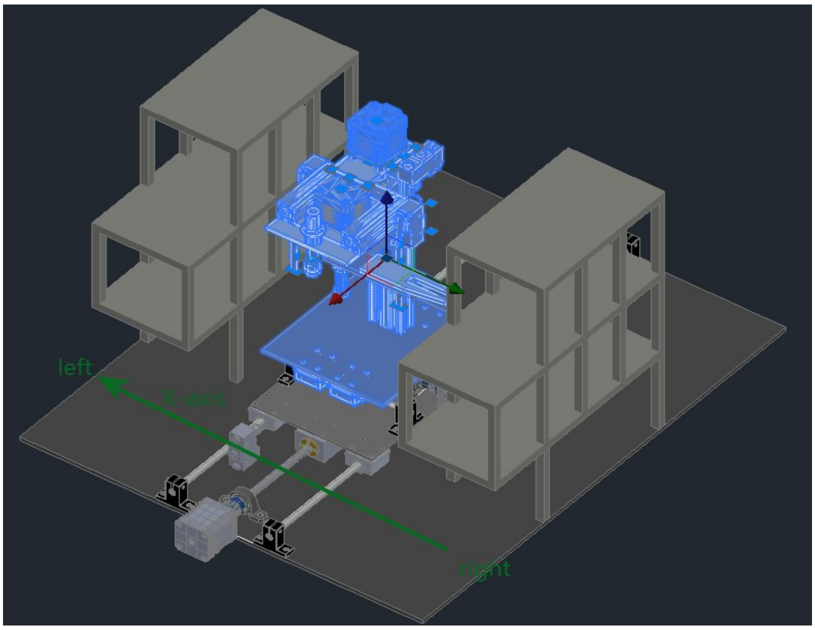


Figure 104. Shift the system to the left to avoid a collision

Consequently, the system has to execute more movements to avoid a collision.

7.3 Improvements

The solution to the collision issue is indeed complexed. There are several ways, but the most optimal approach proposed by the author would be to remove the rotation axis (T-axis). The S/R machine in the project lacks the "telescopic forks" (displayed in Figure 105 and Figure 106), which is a crucial component to carry the item on its carriage towards the cell firmly. The X-axis should be replaced with this fork module, while the movement of the Y-axis and Z-axis might remain the same. The movement of the fork is complexed, but it is constructive and efficient. Accordingly, the "telescopic forks" has become an irreplaceable part of the S/R machine in practice.

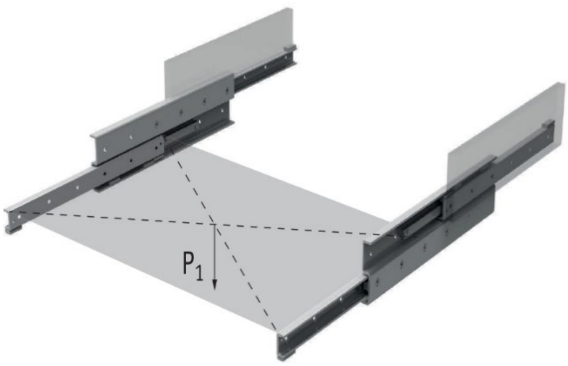


Figure 105. Telescopic forks (Linear Motion Tips, 2017)

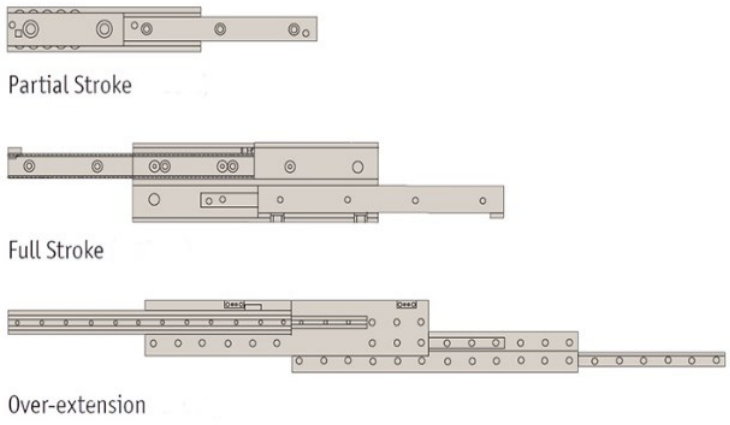


Figure 106. Three different types of telescopic forks (Linear Motion Tips, 2017)

Moreover, even though the movement of the Y and Z axes might stay the same, the mechanism for their linear motion must be replaced due to the impracticability of leadscrew on large scale. The Y-axis should be replaced with high precision guide rails, rack and pinion system (shown in Figure 107 and Figure 108). This system would allow easier installation/replacement with an unlimited length for the Y-axis. Furthermore, cable carrier replacement would also increase the mobility of the system. For the Z-axis, a crane structure with a pulley system is recommended (as illustrated in Figure 109). However, safety clamps must also be installed since this works as a braking system. If a power outage event occurs, a safety-clamp system will kick in to hold the load from falling.

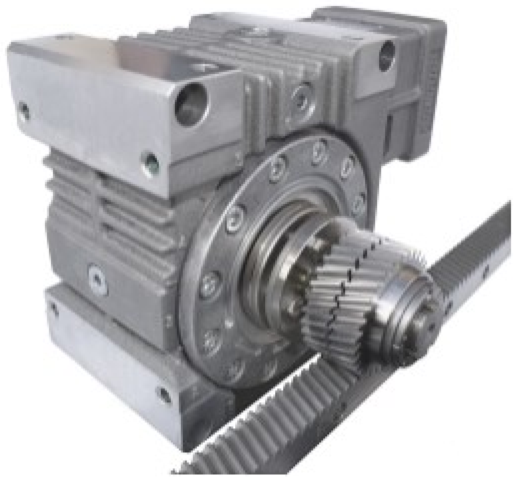


Figure 107. Precision Pinion for Y-axis (Atlantadrives, n.d.)

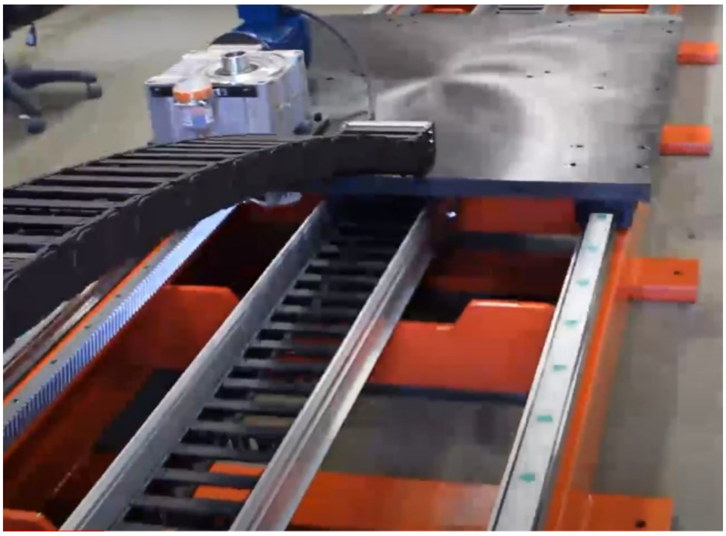


Figure 108. Rack and pinion system for the Y-axis (Lazerarc, 2017)

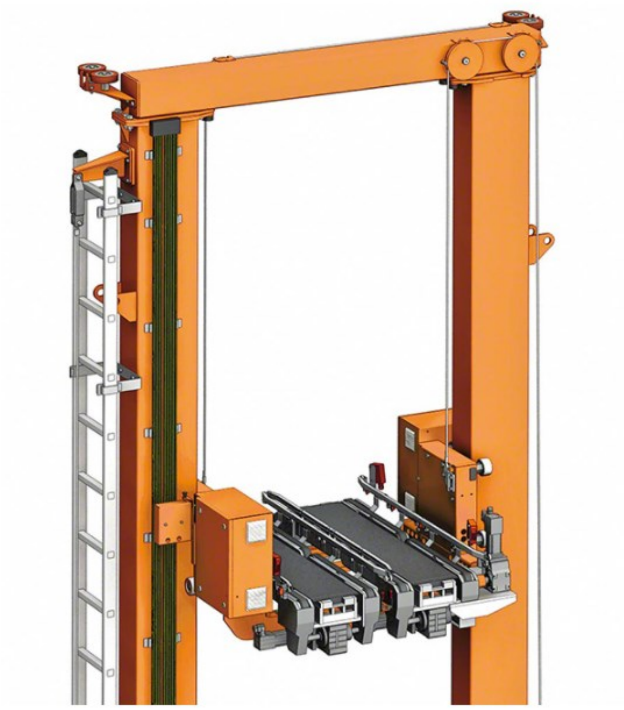


Figure 109. Example structure of Z-axis (Linearmotiontips, 2017)

Figure 110 depicts a simple visualization of the AS/RS for the commissioning party in the stage future of the project. This system not only diminishes the space and the number of movements, but also reduces the number of limit switches or sensors. Moreover, designing electrical implementation and writing PLC programming is much less complicated.

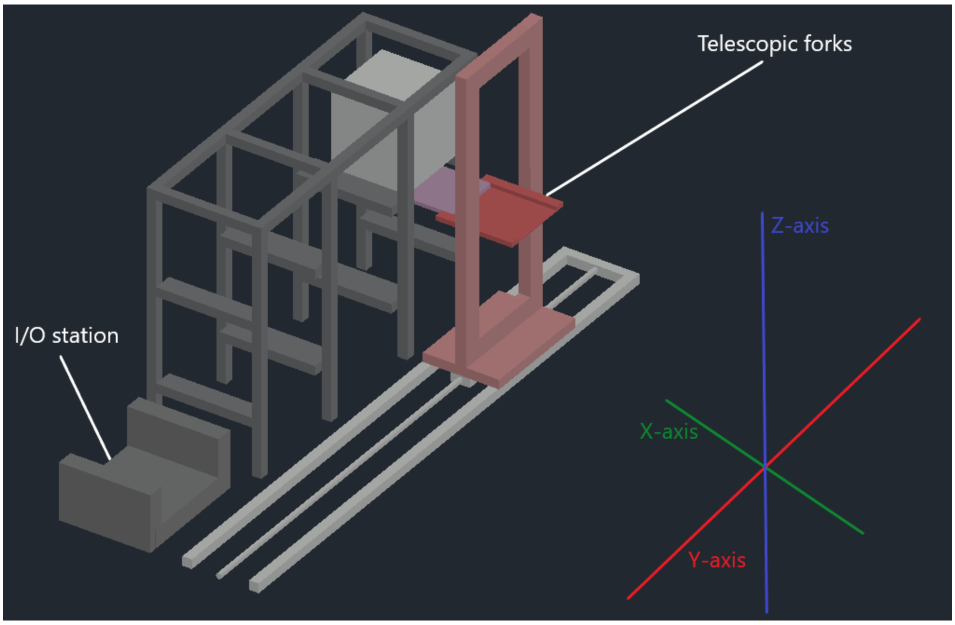


Figure 110. A simple depiction of the proposed AS/RS

In addition, a closed-loop motor is advisable in order to obtain precise movement.

Since many components in this project were used as alternatives for missing components, the operation procedure was not optimal. As a result, the best solution would be to rebuild the system. That will depend on the decision of the commissioning party on whether to invest into further research and the appropriate equipment.

8 CONCLUSION

This thesis has outlined a simple grasp of an Automated Storage and Retrieval System and its general layout. For a greater depth of understanding, a small-scale practice-based model was conducted as a project of the commissioning party. In practice, owing to the significantly high cost and complexity, it was crucial and challenging to design such a system since the AS/RS needs to operate efficiently in cooperation with other systems in the warehouse. Therefore, within the scope of the thesis project, only the design of the layout, controller, programming and user interface for the project were implemented without considering any other factors.

The layout of the system is described based on the mechanical and electrical design in the thesis, where each component is listed and the system mechanism is depicted. The difficulties in handling the project were the lack of some components and limit switches provided by the commissioning party. Therefore, the layout design and PLC programming had to be adapted to these changes. The 3D drawing and the electrical diagram were designed by using AutoCAD Electrical. As required, Ladder Logic Diagram was the primary programming language used in this project. Ladder logic, which is one of the most common types of logic, is constructive and easy for the readers of this thesis and the commissioning party to understand and follow.

Despite the lack of components, the final AS/RS model was approved by the commissioning party based on its feasibility and implementation. However, a challenge lies ahead in the next phase of this project. More research and investment are needed in order to widen the scale of the AS/RS in the warehouse.

REFERENCES

ABB. (2013, January). Comparison of tripping characteristics for miniature circuit-breakers. Retrieved September 4, 2020, from https://library.e.abb.com/public/114371fcc8e0456096db42d614bead67/2CDC400002D0201_view.pdf

ABB. (n.d.). *S201-B16*. Retrieved September 4, 2020, from abb: https://new.abb.com/products/2CDS251001R1165/miniature-circuit-breaker-s200-1p-b-16-ampere

ABSSAC. (n.d.). *Power Lead Screws*. Retrieved October 14, 2020, from ABSSAC: https://www.abssac.co.uk/c/Power+Lead+Screws/14/

Acamley, P. (2002). *Stepping motors - a guide to theory and practice.* (D. P. Atherton, & G. W. Irwin, Eds.) London, United Kingdom: The institution of Engineering and Technology. doi:10.1049/PBCE063E

AliExpress. (n.d.). *Bearing Passive Round Wheel Perlin Wheel V-slot V-type C-Beam*. Retrieved September 26, 2020, from AliExpress: https://www.aliexpress.com/i/32621936426.html

Aliexpress. (n.d.). *Emergency stop switch button LA38/203 209B*. Retrieved October 8, 2020, from Aliexpress: https://www.aliexpress.com/item/1005001418698060.html

Amazon. (n.d.). *SHZOND 2PCS Linear Rail 0.78-47 Inch SBR Linear Guide Rail with 4PCS Bearing Block Linear Rail Set Slide Guide Rod for DIY CNC Routers Lathes Mills*. Retrieved October 14, 2020, from Amazon: https://www.amazon.com/SHZOND-Linear-0-78-47-Bearing-Routers/dp/B07DYQS23Q

Atlantadrives. (n.d.). Retrieved October 27, 2020, from Atlantadrives: https://www.atlantadrives.com/app-rp2.htm

Bakker, B. d. (2018). *TB6600 Stepper Motor Driver with Arduino Tutorial*. (B. d. Bakker, Editor) Retrieved September 3, 2020, from Makerguides: https://www.makerguides.com/tb6600-stepper-motor-driver-arduino-tutorial/

Banggood. (n.d.). *Machifit 500mm 2040 V-Slot Aluminum*. Retrieved September 26, 2020, from Banggood: https://sea.banggood.com/Machifit-500mm-2040-V-Slot-Aluminum-Profile-Extrusion-Frame-DIY-CNC-Tool-Black-p-1295974.html?cur_warehouse=CN

Buildbotics. (2019, Sep 3). *How to Wire Stepper Motors*. (D. Coffland, Editor) Retrieved October 5, 2020, from Buildbotics: https://buildbotics.com/wiring-stepper-motors/

Cadivi-vn. (n.d.). *Instruction of choosing wire and cable*. Retrieved October 10, 2020, from cadivi-vn: http://cadivi-vn.com/vn/huong-dan-lua-chon-day-va-cap-ha-the.html

Cameron, D. E. (1990). *Origin and reduction of acoustic noise in variable reluctance motors.* Bachelor thesis, Massachusetts Institute of Technology, Electrical Engineering and Computer Science, Massachusetts. Retrieved September 3, 2020, from https://core.ac.uk/download/pdf/4422073.pdf

Collins, D. (2017). *Pulley balancing for belt drives*. Retrieved October 14, 2020, from Linearmotiontips: https://www.linearmotiontips.com/pulley-balancing-belt-drives-always-necessary/

Collins, D. (2018, September 22). *How does the number of stator phases affect stepper motor performance?* (D. Collins, Editor) Retrieved Sep 5, 2020, from Linear Motion Tips: https://www.linearmotiontips.com/how-does-the-number-of-stator-phases-affect-stepper-motor-performance/#:~:text=When%20the%20stator%20phases%20are,step%20angle%20of%201.8%20degrees.&text=This%202%2Dphase%20stepper%20has%20eight%20poles

Collins, D. (2018, August 10). *What benefits do dovetail slides offer versus other linear bearing types*. (D. Collins, Editor) Retrieved October 14, 2020, from Linear Motion Tips: https://www.linearmotiontips.com/what-benefits-do-dovetail-slides-offer-versus-other-linear-bearing-types/

Conveyco. (2019, November). 20 Warehouse Automation Statistics That'll Blow Your Mind. (E. Romaine, Ed.) Retrieved September 25, 2020, from https://www.conveyco.com/warehouse-automation-statistics/

Dematic. (2016). Dematic. *Dematic RapidStore ASRS*. Retrieved September 23, 2020, from STORAGE SYSTEMS: Unit Load AS/RS: https://pages.dematic.com/assets/view-ung/?map=10&id=322

DFRobot. (n.d.). TB6600 Stepper Motor Driver User Guide. Retrieved September 3, 2020, from https://www.makerguides.com/wp-content/uploads/2019/10/TB6600-Manual.pdf

Electronics Stack Exchange. (2012, January 11). (Zebonaut, Editor) Retrieved October 5, 2020, from Electronics Stack Exchange: https://electronics.stackexchange.com/questions/24848/how-to-find-out-whether-i-have-a-unipolar-or-a-bipolar-stepper-motor

Electronics Tutorials. (n.d.). *PN Junction Theory*. Retrieved October 8, 2020, from Electronics Tutorials: https://www.electronics-tutorials.ws/diode/diode_2.html

Eminebea. (n.d.). Stepping motor. Retrieved October 6, 2020, from https://www.eminebea.com/en/product/rotary/steppingmotor/hybrid/standard/__icsFiles/afieldfile/2017/09/29/17pm-k_1.pdf

Encyclopaedia Britannica. (n.d.). *Rack and pinion*. Retrieved October 14, 2020, from Encyclopaedia Britannica: https://www.britannica.com/technology/rack-and-pinion

Erectastep. (2020). *Aluminum or Steel: Which Metal is Better?* Retrieved September 27, 2020, from Erectastep: https://www.erectastep.com/aluminum-steel-metal-better/

Ferretto Group. (2019). *automated storage and retrieval systems*. Retrieved September 29, 2020, from ferrettogroup: https://www.ferrettogroup.com/uploads/MediaGalleryPagine//asrs-palletandbins-ferretto-22.PNG

Ferretto Group. (2019). *automated storage and retrieval systems*. Retrieved September 29, 2020, from ferrettogroup: https://www.ferrettogroup.com/index.cfm/en/solutions/asrs/

Groover, M. P. (2016). *Automation, production systems, computer-integrated manufacturing.* Pearson. doi:9781292076119. 9781292076126.

H.Nichols, D. (2018). *Physics for Technology.* CRC Press. Retrieved October 13, 2020, from https://www.ebooks.com/en-us/book/209555483/physics-for-technology-second-edition/daniel-h-nichols/

Harris, M. R., Andjargholi, V., Lawrenson, P. J., Hughes, A., & Ertan, B. (1977). *Unifying approach to the static torque of stepping-motor structures.* Institution of Electrical Engineer. doi:10.1049/piee.1977.0254

Ikont. (n.d.). *Product*. Retrieved October 14, 2020, from Ikont.co.jp: https://www.ikont.co.jp/eg/product/chocudo/chc34.html

Innovating Automation. (n.d.). *An Easy Way to Remember PNP and NPN Sensor Wiring*. (Balluff Inc) Retrieved October 8, 2020, from Innovating Automation: https://www.innovating-automation.blog/an-easy-way-to-remember-pnp-and-npn-sensor-wiring/

Kardex remstar. (2018). *7 Types of Automated Storage and Retrieval Systems (ASRS): A Deep Dive*. (C. Tarr, Editor) Retrieved September 29, 2020, from Kardex remstar: https://us.blog.kardex-remstar.com/types-of-automated-storage-and-retrieval-systems

Kliber, T. (2015, July 20). *Choose the best linear positioning device for your application*. (T. Kilber, Editor, & Nexen Group) Retrieved October 14, 2020, from Linear

Motion Tips: https://www.linearmotiontips.com/choose-the-best-linear-positioning-device-for-your-application/

Ladder Logic WORLD. (2020, September 28). *Ladder Logic Basics*. Retrieved from Ladder Logic WORLD: https://ladderlogicworld.com/ladder-logic-basics/

Lan, J. (2013). *Design and Fabrication of a Modular Multi-Material 3D Printer.* Master thesis, Massachusetts Institute of Technology, Mechanical Engineering, Massachusetts. Retrieved October 14, 2020, from https://core.ac.uk/download/pdf/18320933.pdf

Lazerarc. (2017, August). *Guide to linear robot transfer units*. Retrieved October 25, 2020, from Lazerarc: https://resources.lazerarc.com/guide-to-robot-transfer-units-rtu#markets_and_applications_for_linear_robot_transfer_units

Lead Screw or Belt-Drives. (n.d.). Retrieved October 13, 2020, from PBC Linear: https://www.pbclinear.com/Blog/2020/February/Lead-Screw-or-Belt-Drives

Linear Motion Tips. (2017). *Telescoping slides: Extending the reach of linear guides*. (D. Collins, Editor) Retrieved October 27, 2020, from Linear Motion Tips: https://www.linearmotiontips.com/telescoping-slides-extending-the-reach-of-linear-guides/

Linearmotiontips. (2017, June 20). *Vertical linear motion: Hoists to lifts to AS/RS reach new heights*. (Interlake Mecalux) Retrieved October 25, 2020, from Linearmotiontips: https://www.linearmotiontips.com/vertical-linear-motion-hoists-lifts-asrs-reach-new-heights/

Logistics Management. (2019, May 15). Annual Warehouse and Distribution Center Automation Survey: More automation, please. (B. McCrea, Ed.) Retrieved September 18, 2020, from https://www.logisticsmgmt.com/article/annual_warehouse_and_distribution_center_automation_survey_more_automation

Makeralot. (n.d.). *2020 V-slot aluminium extrusion*. Retrieved September 26, 2020, from Makeralot: https://www.makeralot.com/2020-v-slot-aluminium-extrusion-1-meter-p211/

Manzini, R. (2012). *Warehousing in the Global Supply Chain.* Bologna: Springer. doi:10.1007/978-1-4471-2274-6

Mecholic. (n.d.). *What Is Chain Drive? Advantages and Disadvantages of chain drive over Belt and Rope Drive*. Retrieved October 14, 2020, from Mecholic: https://www.mecholic.com/2018/10/what-is-chain-drive-advantages.html

Medical Design and Outsourcing. (2016). *What are ball screws?* (N. Abraham, Editor) Retrieved October 14, 2020, from Medical Design and Outsourcing: https://www.medicaldesignandoutsourcing.com/what-are-ball-screws/

Misumi. (n.d.). *Cross roller table*. Retrieved October 14, 2020, from uk.misumi-ec.com: https://uk.misumi-ec.com/vona2/detail/221000089439/?HissuCode=VRU4165

NJR. (n.d.). *Stepper Motor Basics.* Retrieved September 3, 2020, from NJR: https://www.njr.com/electronic_device/PDF/application_notes/Stepper_Motor_Basics_APP_E.pdf

NPM. (n.d.). *THE DIFFERENCE BETWEEN: Unipolar and Bipolar.* Retrieved October 5, 2020, from NPM: https://www.nipponpulse.com/assets/files/MD%20Difference%20Between%20-%20Steppers.pdf

Omnicable. (n.d.). *Basics of wire and cable.* Retrieved October 10, 2020, from Omnicable: https://www.omnicable.com/cable-services/cable-knowledge/2017/05/25/basics-of-wire-and-cable-solid-vs.-stranded-conductors

Onsemi. (n.d.). *TIP41A / TIP41B / TIP41C NPN Epitaxial Silicon Transistor*. Retrieved October 8, 2020, from Onsemi: https://www.onsemi.com/pub/Collateral/TIP41C-D.PDF

Opencircuitshop. (n.d.). *LJ12A3-4-Z/BX PROXIMITY SENSOR N/O NPN 4MM*. Retrieved October 8, 2020, from Opencircuitshop: https://opencircuit.shop/Product/LJ12A3-4-Z-BX-Proximity-sensor-N-O-NPN-4mm

Pinterest. (2020). *Why NPN Transistors are mostly used than PNP Transistors?* Retrieved October 8, 2020, from Pinterest: https://www.pinterest.co.uk/pin/719309371716284609/

Reisch, M. (2003). *High-Frequency Bipolar Transistors* (1 ed.). Springer-Verlag Berlin Heidelberg. doi:10.1007/978-3-642-55900-6

Siemens. (2015). SIMATIC S7-1200 Manual. Retrieved September 3, 2020, from https://support.industry.siemens.com/cs/document/39710145/simatic-s7-1200-easy-book?dti=0&lc=en-WW

Siemens. (2017). *Programming with STEP 7*. Retrieved October 3, 2020, from Siemens: https://cache.industry.siemens.com/dl/files/825/109751825/att_933142/v1/STEP_7_-_Programming_with_STEP_7.pdf

Siemens. (2020). 6ES7214-1AG31-0XB0. Retrieved October 7, 2020, from https://mall.industry.siemens.com/mall/en/WW/Catalog/Product/6ES7214-1AG31-0XB0

thegioiic. (n.d.). *LXW5-11G2*. Retrieved October 8, 2020, from thegioiic: https://www.thegioiic.com/products/lxw5-11g2-cong-tac-hanh-trinh-380vac-10a

THK. (n.d.). *Flat Roller*. Retrieved October 14, 2020, from THK: https://www.thk.com/?q=uk/node/4542

THK. (n.d.). *Linear Bushing*. Retrieved October 14, 2020, from THK: https://www.thk.com/?q=eng/node/237

Thomson. (n.d.). *What is the difference between pitch and lead when referring to a screw?* Retrieved October 14, 2020, from Thomson: https://www.thomsonlinear.com/en/support/tips/what-is-the-difference-between-pitch-and-lead-when-referring-to-a-screw

WAP. (2018). *shuttle-carrier-storage-system*. Retrieved September 29, 2020, from wapshanghai: https://www.wapshanghai.com/

Wennrich, P. (2019). *International dictionary of abbreviations and acronyms of electronics, electrical engineering, computer technology, and information processing: Vol. 1: A - I. Vol. 2: J - Z.* Walter de Gruyter GmbH & Co KG. Retrieved October 6, 2020, from https://books.google.com.vn/books?id=CFaSDwAAQBAJ&dq=transistor+transfer+resistor+acronym&source=gbs_navlinks_s

Wenzelmetalspinning. (n.d.). *Steel versus aluminum weight, strength, cost,malleability comparison*. Retrieved September 27, 2020, from Wenzelmetalspinning: https://www.wenzelmetalspinning.com/steel-vs-aluminum.html#:~:text=Even%20with%20the%20possibility%20of%20corrosion%2C%20steel%20is%20harder%20than%20aluminum.&text=Steel%20is%20strong%20and%20less,2.5%20times%20denser%20than%20aluminum.

WikiBooks. (n.d.). *Semiconductors/Introduce to Transistor*. Retrieved October 8, 2020, from WikiBooks: https://en.wikibooks.org/wiki/Semiconductors/Introduce_to_Transistor

Retrieve left

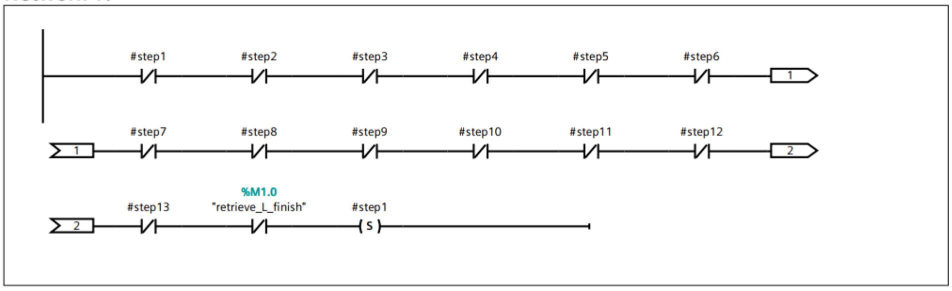
Block title: .....

retrieve the item from the left shelf.
Item initial position: chosen cell
Item final position: I/O station

Network 1:

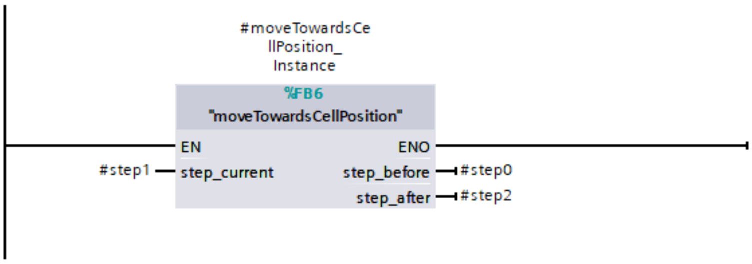
track the current step. the initial step is 1

Network 1:



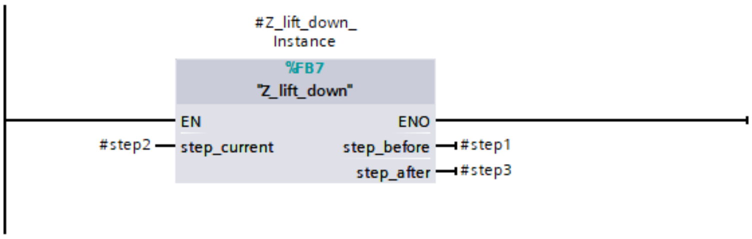
Network 2: y forward and (z down if lower cell)

move the item towards the chosen cell position



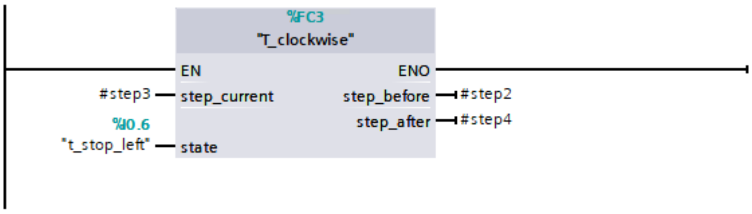
Network 3: z down

later, lift up at Network 6



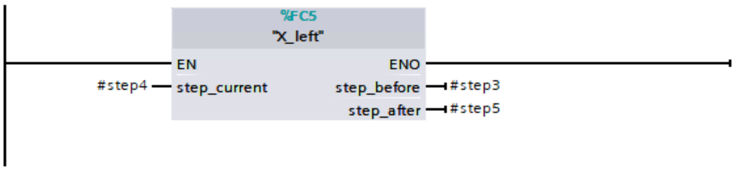
Network 4: .....

rotate T to left position



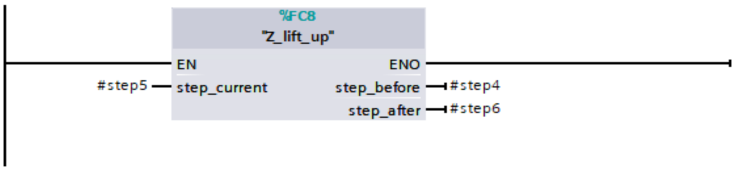
Network 5: x left

move fork towards the item



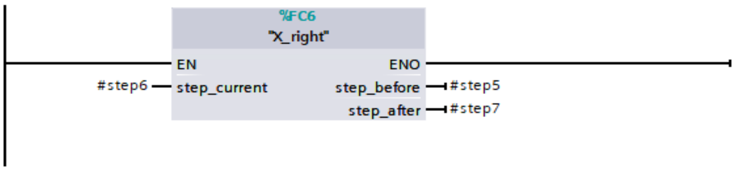
Network 6: z up

lift the item up



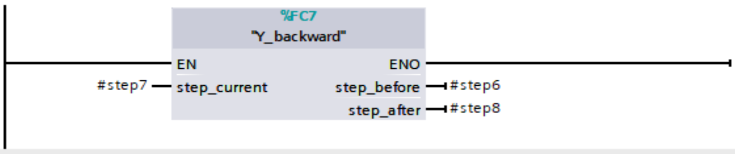
Network 7: x right

move the item out of the "I/O station"



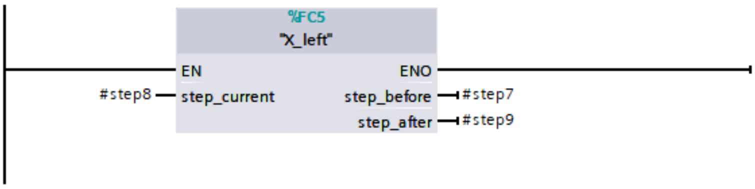
Network 8: y backward

-> I/O station



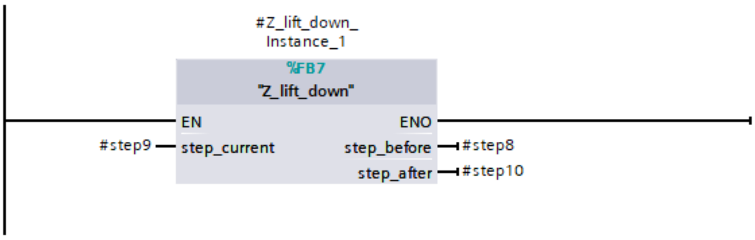
Network 9: x left

move the item towards the I/O station



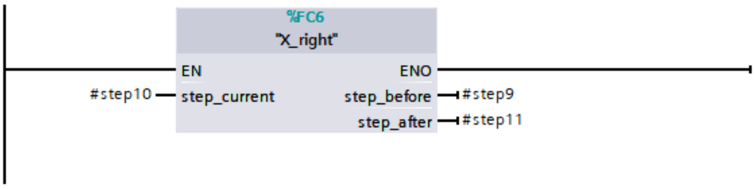
Network 10: z down

place the item at the I/O station, reserve space to move the fork out



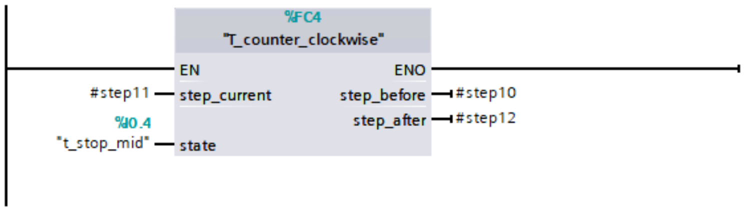
Network 11: x right

move the fork out of the item



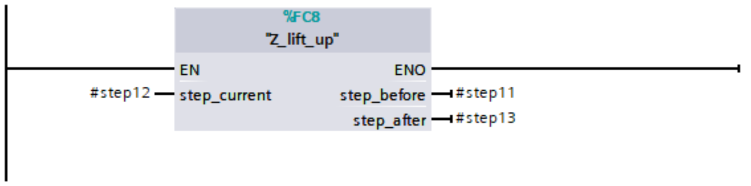
Network 12: .....

rotate T to mid position -> home position



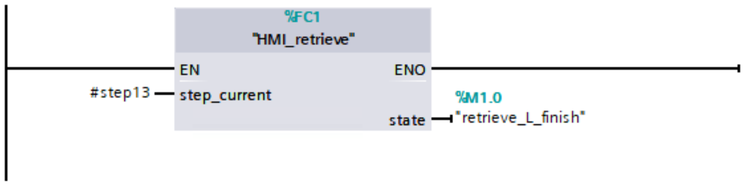
Network 13: z up

-> home position



Network 14: .....

set "retrieve_L_finish" to 1
set chosen cell status to 0 (light on HMI off)



Appendix 2(1)

Store left

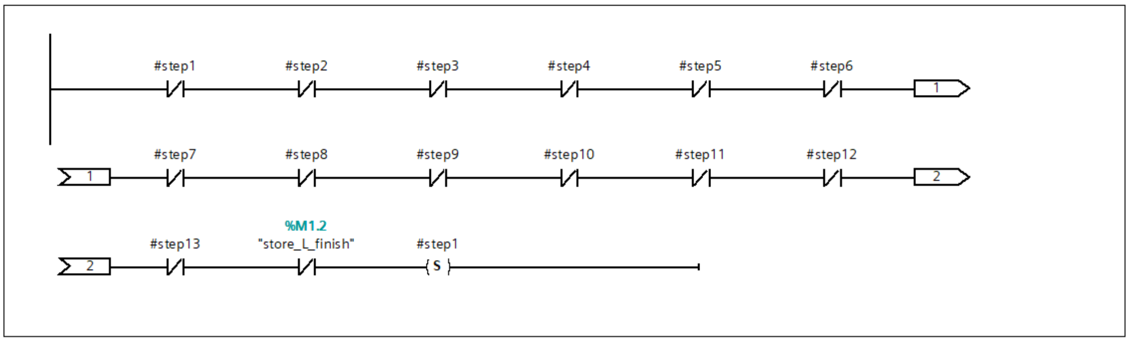
Block title: .....

store the item to the left shelf.
Item initial position: I/O station
Item final position: chosen cell

Network 1:

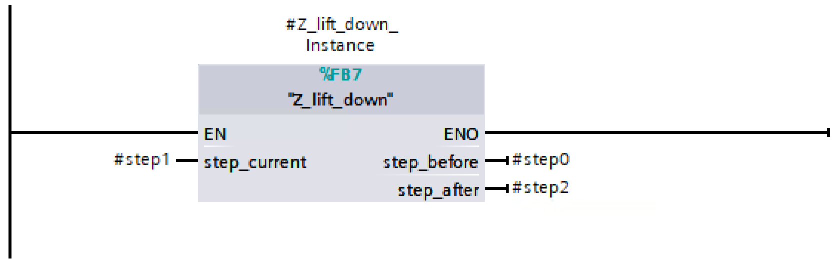
start at step 1

Network 1:



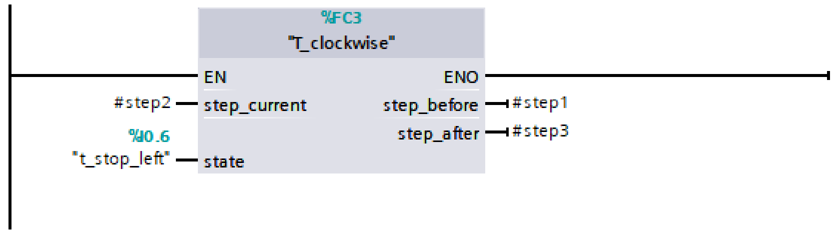
Network 2: z down

later, lift up at Network 5



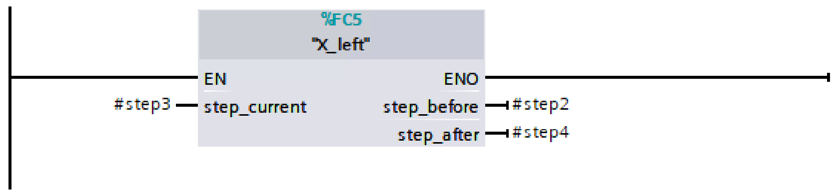
Network 3: .....

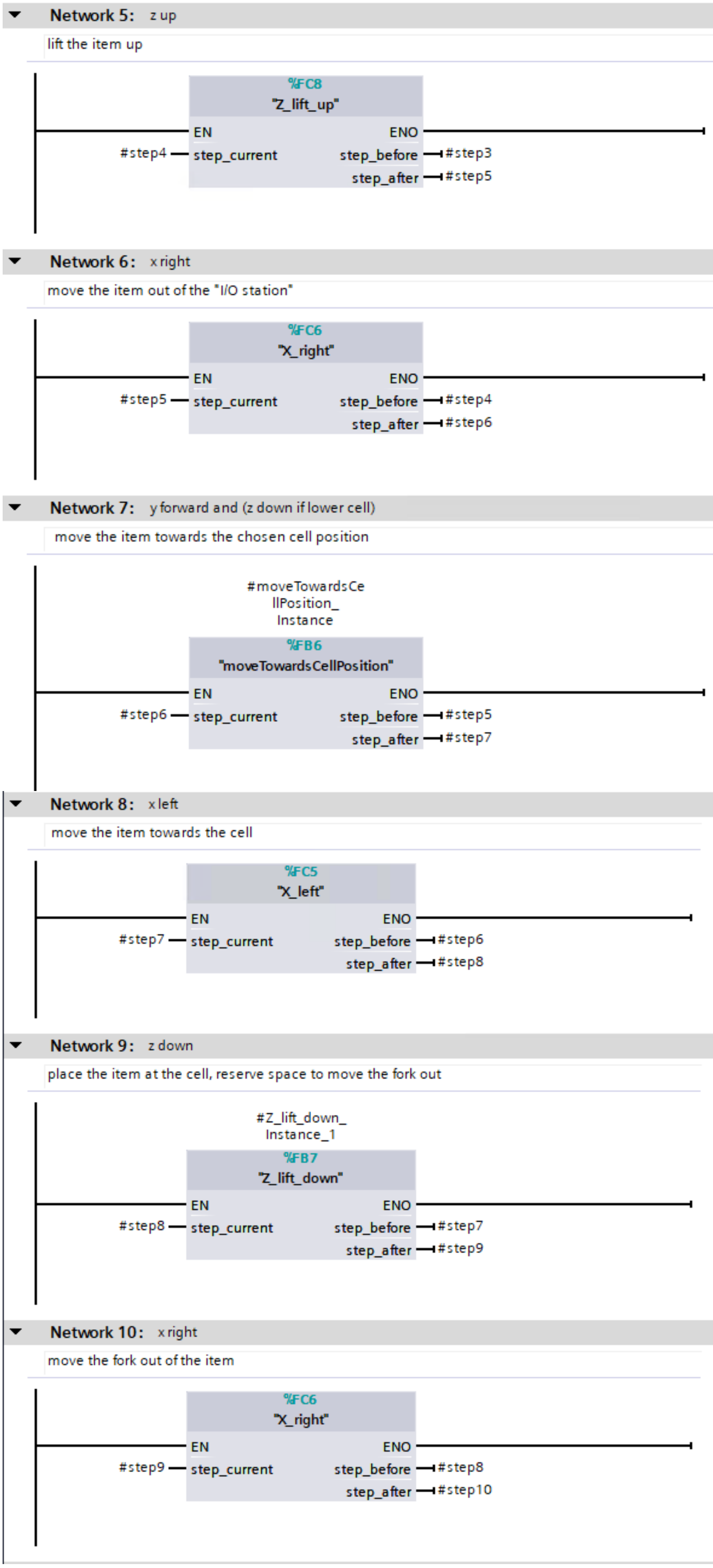
rotate T to left position

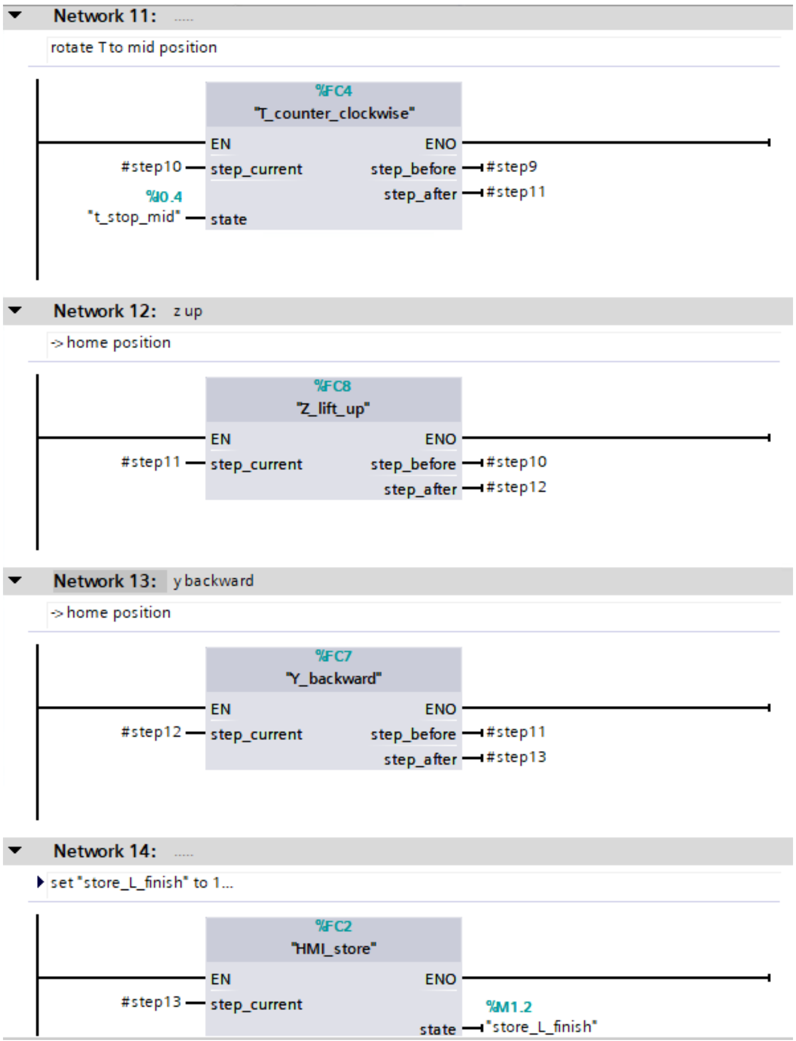


Network 4: x left

move fork towards the item




Network 5: z up
lift the item up
%FC8
"Z_lift_up"
EN
ENO
#step4
step_current
step_before
#step3
step_after
#step5
Network 6: x right
move the item out of the "I/O station"
%FC6
"X_right"
EN
ENO
#step5
step_current
step_before
#step4
step_after
#step6
Network 7: y forward and (z down if lower cell)
move the item towards the chosen cell position
#moveTowardsCe
llPosition_
Instance
%FB6
"moveTowardsCellPosition"
EN
ENO
#step6
step_current
step_before
#step5
step_after
#step7
Network 8: x left
move the item towards the cell
%FC5
"X_left"
EN
ENO
#step7
step_current
step_before
#step6
step_after
#step8
Network 9: z down
place the item at the cell, reserve space to move the fork out
#Z_lift_down_
Instance_1
%FB7
"Z_lift_down"
EN
ENO
#step8
step_current
step_before
#step7
step_after
#step9
Network 10: x right
move the fork out of the item
%FC6
"X_right"
EN
ENO
#step9
step_current
step_before
#step8
step_after
#step10


Network 11: .....
rotate T to mid position
%FC4
"T_counter_clockwise"
EN
ENO
#step10
step_current
step_before
#step9
step_after
#step11
%I0.4
"t_stop_mid"
state
Network 12: z up
-> home position
%FC8
"Z_lift_up"
EN
ENO
#step11
step_current
step_before
#step10
step_after
#step12
Network 13: y backward
-> home position
%FC7
"Y_backward"
EN
ENO
#step12
step_current
step_before
#step11
step_after
#step13
Network 14: .....
set "store_L_finish" to 1...
%FC2
"HMI_store"
EN
ENO
#step13
step_current
%M1.2
state
"store_L_finish"